ECE110 *Introduction to Electronics*

What is…?

ECE

ECE110

Charge

Current

Voltage

Power

Energy

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DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

The Field of Study Defined

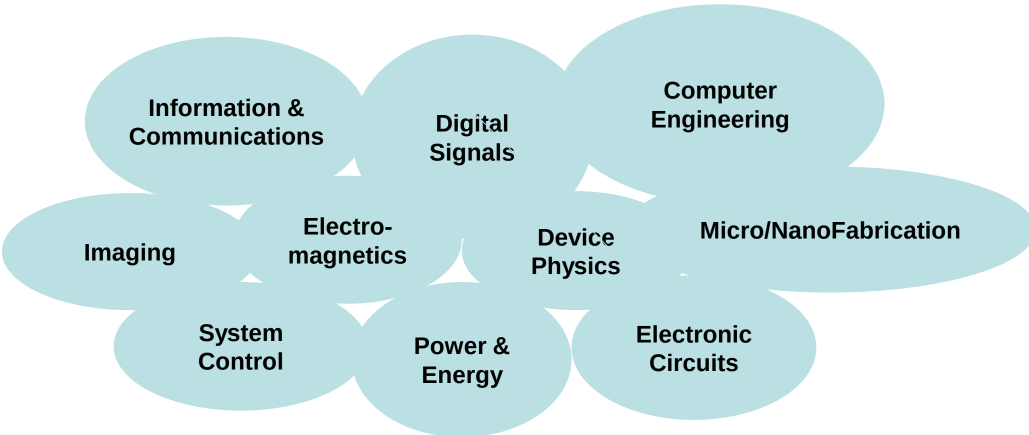
"***Engineers*** use the knowledge of mathematics and natural sciences gained by study, experience, and practice, applied with judgment, to develop ways to economically utilize the materials and forces of nature for the benefit of mankind. "

- ABET (Accreditation Board for Engineering and Technology)

Electrical engineering (EE) is a field of **engineering** that generally deals with the study and application of electricity, electronics, and electromagnetism

- WikiPedia

Electrical Engineering inseparable focus areas



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ECE110 introduces EE with a focus on electronics

You will:

- **measure** electrical devices
- **analyze** and **model** electrical circuits
- **construct** electrical systems
- **design** a control system for your own autonomous vehicle
- **create** your own "open-ended" project

The laboratory provides a hands-on opportunity to showcase your skills!

Charge and Current

- an electron is a charged subatomic particle
- the coulomb (C) is a measure of electric charge with

$$\frac{-1.6 \times 10^{-19} C}{electron} \underset{=}{(notation)} \frac{-1.6\,\mathrm{e}-19\ C}{electron}$$

- Electric current is the flow of electric charge in time (C/s)

$I = \Delta Q / \Delta t$ the Δ means "the change in"

- The ampere is the unit of electric current

$1\ A = 1\ C/s$

Image is public domain.

Q2 Answers:

A. 0.00000016 A
B. 0.160 A
C. 1 A
D. 1e-9 A
E. 160e-12 A

L1Q1: What is the charge of 1 billion electrons?

L1Q2: A "typical" electronics circuit might have 1 billion electrons pass a cross section of a wire every nanosecond, what is the electric current in amps?

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Voltage and Energy

- **Energy** is **the ability to do work**, measured in joules (J), BTUs, calories, kWh, etc.
- **Voltage** is **the work done per unit charge** (eg. J/C) against a static electric field to move charge between two points
- Also, 1 volt $(1\ V)$ is the electric potential difference between two points that will impart $1\ J$ of energy per coulomb $(1\ C)$ of charge that passes through it.

$$\Delta E = \Delta Q \times V$$

L1Q3: A certain battery imparts 480 pJ to every 1 billion electrons. What is its voltage?

L1Q4: What is the charge moved through 400 V (EV battery) to provide 800 kJ of energy?

L1Q5: What is the average current if the energy in Q4 is provided in five seconds?

Energy and Power

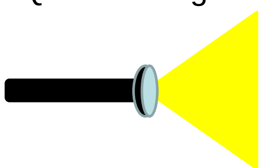
Power is **the rate at which energy is transferred**.

Power is $(rate\ of\ charge\ flow) \times (potential\ difference)$

Power is $current \times voltage$

$$P = \frac{\Delta E}{\Delta t} = \frac{\Delta Q}{\Delta t} V = I\ V$$

L1Q6: A flashlight bulb dissipates $6\ W$ at $2\ A$. What is the supplied voltage?



Required

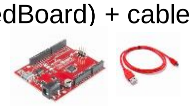
- ECE Supply Center
  - ECE110 Electronics Kit

    Beware: Significant changes from past!
  - i>clicker
- Online (courses.engr.Illinois.edu/ece110)
  - ECE110 Lecture Slides
  - ECE110 Lab Procedures
  - Weekly PrairieLearn Assignments
  - Course Piazza Announcements
  - Online Textbook (Course Notes)
  - Critical Course Videos

AND/OR

Recommended

- ECE Supply Center
  - Voltmeter
  - Multipurpose wire stripper
  - Arduino (or RedBoard) + cable



- IUB Bookstore
  - ECE 110 Lecture Slides
  - ECE 110 Lab Procedures
- Online
  - Extra examples, videos, etc.

Assignments

- Homework
  - Online via **PrairieLearn**
  - Due **Fridays at 3 pm**. Get it done early!
  - Discuss on **Piazza**. When posting/replying publicly, **ask for resources** and not detailed solutions.
  - If you need help on your **detailed** solution, post a **private** question to the instructors.
  - Multiple opportunities to earn credit on each problem. Everyone should get 100% on homework!
  - Absolutely **no submissions past the credit dates** (start early if you plan to be sick on Fridays ☺)
  - To get help in **office hours**, bring your solution *on paper*!
- Lab
  - Weekly meetings
  - Enter from the "lecture side", room 1005 ECEB
  - Move to 1001 ECEB after TA has instructed you
  - Does not meet the week of Spring/Fall Break nor the week of the MLK holiday or Labor Day holiday.
  - Prelab assignments due at the beginning of your meeting
  - Lab summary is submitted at the end of each lab period, periodic Unit Reports

Recommended learning opportunities

- **Workshops** (as announced each week)
- **Office Hours** Room 1005 (near lab), Monday-Friday
- **CARE** Grainger Library
- **Honors projects** targeting James Scholars, ECE110+ECE120

Encountering various difficulties? Contact your Instructor, lab TA, or the advising office on the second floor (2120 ECEB)!

Grading policies

A+	Greater than 97%
A	93-97%
A-	90-93%
B+	87-90%
B	83-87%
B-	80-83%
C+	77-80%
C	73-77%
C-	70-73%
D+	67-70%
D	63-67%
D-	60-63%
F	Less than 60%

Laboratory	**30%** [1]
Lecture Total	**70%** [1]
3 midterms	30%
Final Exam	25% [2]
Homework	10%
Attendance	5 %

[1]You must obtain 50% of the lecture score and 50% of the lab score to avoid failing the course!

[2]The Final Exam can have an effective weight of 35% by replacing the lowest midterm grade.

L1 Learning Objectives

a. (L1a) Compute relationships between charge, time, and current.
b. (L1b) Compute relationships between charge, voltage, and energy.
c. (L1c) Compute relationships between power, current, and voltage.

$$I = \frac{\Delta Q}{\Delta t} \qquad V = \frac{\Delta \mathrm{E}}{\Delta Q}$$

$$\Delta E = \Delta Q \times V$$

$$P = \frac{\Delta E}{\Delta t} = \frac{\Delta Q}{\Delta t} V = I\,V$$

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Policies

- Lab attendance is **mandatory**, each and every week
- **No food/drink in 1001 ECEB**
- Food and drink **allowed in 1005 ECEB**, only. Since this room is used for office hours, take your book bag with you into the lab.
- Lecture attendance is semi-mandatory…see next slide

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Feeling Sick? Can't make class?

Please, don't risk infecting others.

Lab: Notify your lab TA (not me!) before lab to request an excused absence. Up to two may be granted.

Lecture: Do nothing. Missed lectures will be counted towards your 20% *excused* absences.

Forgot your i>clicker? Do nothing; will be counted towards your 20% excused absences.

Seeking advice and help?

- **Talk to us!** Instructors, graduate TAs, undergrad course aides want to know you!
- **CARE:** the *Center for Academic Resources in Engineering* provides study periods and tutoring options in many STEM courses.
- ***ECE Advising Office*** (2120 ECEB) provides all kinds of advice. They can also recommend others:
  - **U of I *Counseling Center*** for time management, study skill, test-taking skills, and confidential personal counseling
  - **DRES**: the Disability Resources & Educational Services center for aid in overcoming unique challenges that you may encounter through your education

Lecture 2: A history…
From Charge Storage to Ohm's Law

- A short video
- Capacitors
- Batteries
- Conservation of Energy
- Ohm's Law

Energy Facts

- Conservation of Energy

  $$E_{input} = E_{useful} + E_{waste}$$

- Mechanical Energy

  Kinetic and Potential Energy; Energy vs. Power

- Electrical Energy Storage

  Capacitors and Batteries

Capacitors: store electrical energy

$C = Q/V$ – capacitance is the charge-to-voltage ratio of a capacitor

$$E_{capacitor} = \frac{1}{2}CV^2$$

In History…

The first device for storing electrical energy became known as Leyden Jar after the city in which it was built (1745). It had a capacitance of about 1 nF.

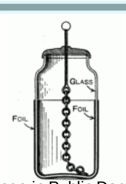


Image in Public Domain

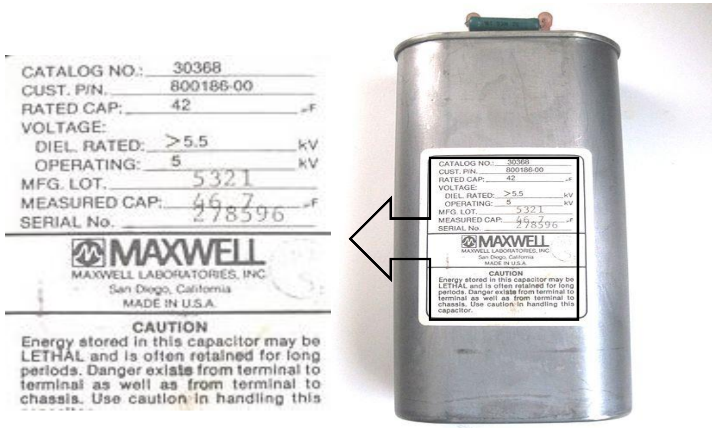
In History…

Yes, **Benjamin Franklin** collected electrostatic charge from a storm using a kite in 1752, but also formulated the *principle of conservation of electric charge* and coined the terms “positive” and “negative” with respect to the charge carriers (current).

L2Q1: At what voltage would a $1\ nF$ capacitor have the energy to lift $100\ kg$ by $2\ cm$?

Special Capacitor: Defibrillator

L2Q2: How much energy, E_{cap}, is in the 42 µF defibrillator capacitor charged to 5 kV?



$E_{cap} =$

A. $5.25\ mJ$
B. $5.25\ J$
C. $525\ J$
D. $525\ MJ$
E. $525\ GJ$

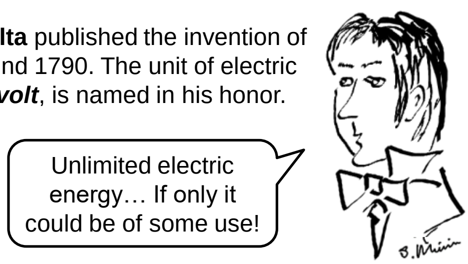
L2Q3: Half of the capacitor's charge, Q, is then drained off. How much energy does it hold now?

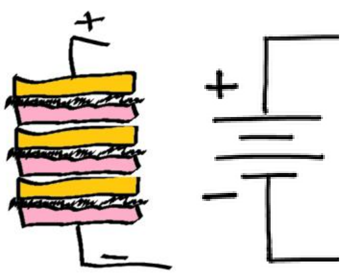
A. $\frac{E_{cap}}{8}$
B. $\frac{E_{cap}}{4}$
C. $\frac{E_{cap}}{2}$
D. E_{cap}
E. $2E_{cap}$

Batteries store and generate electrical energy with a chemical reaction

In History…

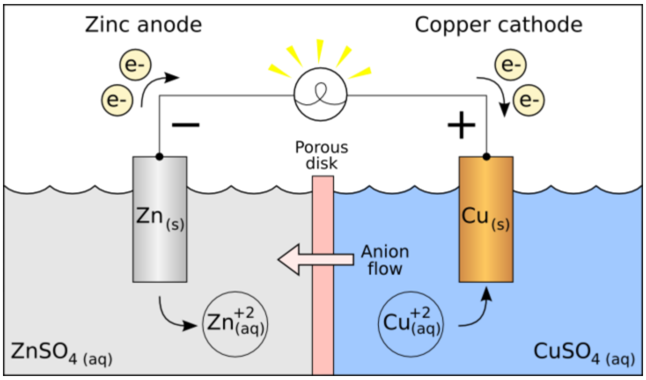
Alessandro Volta published the invention of the battery around 1790. The unit of electric "pressure", the ***volt***, is named in his honor.





L2Q4: How much charge moves through a 9-V battery to provide 3 J of energy?

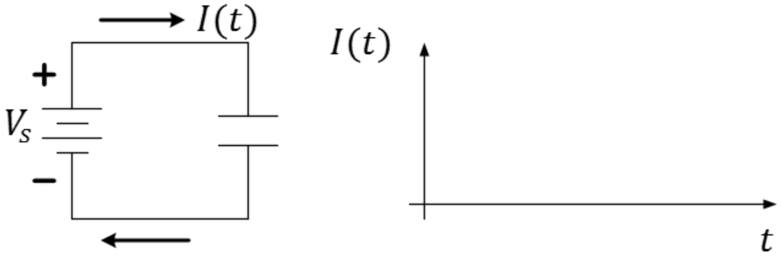
Explore More! Batteries



Read more:
https://en.wikipedia.org/wiki/Galvanic_cell

Chemistry 102 and 103!

Example



- $\Delta E_{battery} = \Delta E_{capacitor} + \Delta E_{waste}$
- $\Delta E_{waste} \geq \frac{1}{2}CV^2$

Physics 212

- $\Delta E_{battery} \approx \frac{1}{2}CV^2 + \frac{1}{2}CV^2 = CV^2$

Batteries and capacitors notes

- The current drawn from a capacitor or battery depends on the *load.*
  - Include wires, light bulbs, LEDs, motors, etc.
  - What limits the maximum current possible?
  - We need simplified *Models* for batteries and loads
- Batteries vs. Capacitors

L2Q5: If a battery is labeled at 9 V and 500 mAh, how much energy does it store?
L2Q6: For how long can such battery power an LED if it draws 50 mA of current?

Ohm's law models the current and voltage relationship in conductors

Motivated by long-distance telegraphy, Georg Ohm (~1825) conducted careful experimentation to find this widely-used approximate mathematical model:

$$I = \frac{V}{R}$$

where $R = \rho \frac{l}{A}$ is resistance of a *conductor* (e.g. wire)

with length, l, and area A, and where ρ is *resistivity* - a material parameter

L2Q7: Find the diameter of one mile of Cu ($\rho = 1.7 \times 10^{-8}\ \Omega\ m$) wire when $R = 10\ \Omega$.
L2Q8: If the resistance of one wire is $10\ \Omega$, what is the resistance of two such wires in parallel?

Resistors are devices that obey Ohm's Law

- Resistors are used to set current when voltage is given
- Resistors are used to set voltage when current is given
- Power is always dissipated in resistors, and they heat up

$$P = I\,V = \frac{V^2}{R} = I^2 R$$

In History…

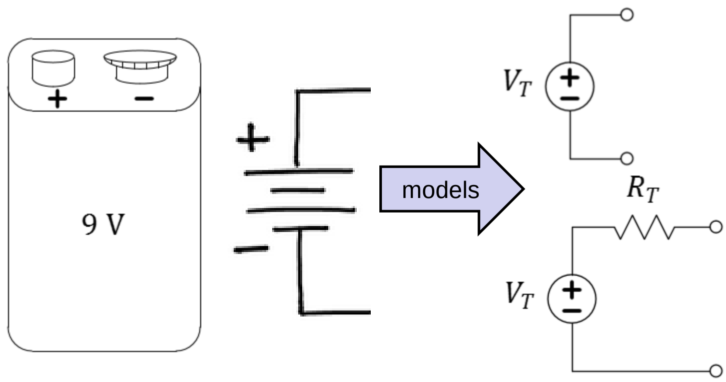
Henry **Cavendish** conducted similar experiments over 40 years earlier than Georg **Ohm** using Leyden jars for voltage sources and the shock felt by his body as an *ad hoc* ammeter!

Image in Public Domain

L2Q9: If a resistor of 100 Ω is rated at 0.25 W, what is its maximum current?
L2Q10: What is the power dissipated by that resistor if there is a 6 V drop across it?

Resistances are used to model devices

- Lengths of wire
- Incandescent bulbs
- Heating elements
- Battery terminals
- Stalled motors
- Fuses, etc.



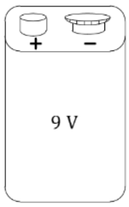
L2Q11: If a 9 V battery provides (at maximum) a current of 2 A, what is its modelled "internal" resistance, R_T?

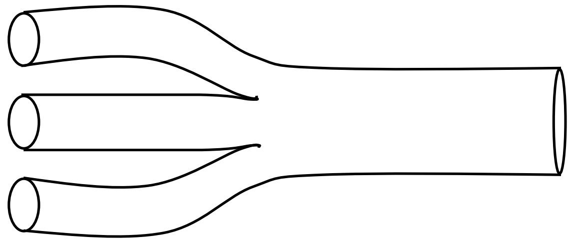
L2Q12: When would you want to use a capacitor over a battery?

A. When you need a burst of high current for short time
B. When you need to power something at a constant current over a long period of time
C. Always, batteries just too expensive compared to caps
D. Never, batteries are better, more expensive than caps
E. I'm kind of getting lost

L2 Learning Objectives

a. (L2a) Solve energy transfer problems involving mechanical potential and kinetic energy as well as efficiency (or wasted energy) considerations.
b. (L2b) Compute power, energy, and time, given two of three.
c. (L2c) For a capacitor, compute stored energy, voltage, charge, and capacitance given any of the two quantities.
d. (L2d) Compute energy stored in a battery and discharge time.
e. (L2e) Compute resistance of a cylindrical conductor given dimensions.
f. (L2f) Relate voltage and current for an "Ohmic" conductor.
g. (L2g) Perform unit conversions for energy, charge, etc.
h. (L2h) Use Ohm's Law to model the internal resistance of a physical battery.





Lecture 3 : Power and Energy

- Announcements
- Avoidance of Ethical Issues
- Power and Energy with examples

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There Should Always be Alignment in a Community

Proactively avoid ethical dilemmas

Picking Up the Slack…search at Santa Clara University:

http://www.scu.edu/

❖ Often called a "hitch-hiker" scenario…

What do you feel Greg should do?

A. Value the relationship, grade Natalie the same as the group.
B. Greg is not a babysitter…give Natalie the grade she earned.
C. Give Natalie a worse grade than the group, but better than she deserved.
D. Talk to Natalie before deciding which grade to give.
E. Talk to the Instructor before deciding which grade to give.

What would you have done?

ECE 316

Recall "Energy"

- Energy is **ability to do work**
- Energy comes in many forms
- Energy is conserved (can change forms)

Examples: heat, light, electrical energy, chemical, mechanical (e.g. potential, kinetic), mass, etc…

What is “work” ?

- drive to Chicago
- move a couch
- cook an egg
- lift a camel
- launch a satellite
- stay awake in lecture (try!)
- electrocute somebody (don’t!)
- send an email (to Brazil or Urbana?)
- *write down some of your own ideas*

Driving to Chicago…accounting

- Distance: 200 km
- Elevation Drop: 44 m
- Where is the waste?

Explore More!

Elon Musk is in the news much these days as Hyperloop One comes on line. What are some benefits of Hyperloop technology? What are some cons?

If $\Delta E_{state} \equiv E_{useful}$, then

$$E_{input} = \Delta E_{state} + E_{waste} = \eta E_{input} + (1-\eta) E_{input}$$

Q1:
A. $8\ mJ$
B. $1\ J$
C. $80\ J$
D. $1\ kJ$
E. $800\ kJ$

L3Q1: How much energy does it take to accelerate a 2200 kg car from 0 to 60 mph?
L3Q2: What is the energy *input* needed if the engine/drive train losses are 70%?
L3Q3: A certain gas car gets 50 km/gal (avg). How much energy does it take to get to Chicago?

Rate of lifting camels – power!

Definition of power: $P = \frac{\Delta E}{\Delta t}$ is rate of energy…

L3Q4: What is the average power needed to lift 500 kg by two meters every minute?

L3Q5: What is the power needed to expend 800 kJ in five seconds?
L3Q6: What is the charge moved through 400 V to provide 800 kJ of energy?
L3Q7: What is the average current if the energy in Q5 is provided in five seconds?

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L3 Learning Objectives

a. (L3a) Develop a plan to avoid an ethical dilemma in the laboratory
b. (L3b) Solve energy transfer problems involving mechanical potential and kinetic energy as well as efficiency (or wasted energy) considerations.
c. (L3c) Compute power, energy, and time, given two of three.

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Lecture 4: Circuit Modelling and Schematics

- Circuit Modeling and Schematics: A resistive heater
- Electromagnetism – Oersted's 1820 demonstration
- Measuring current and moving things that are near and far
- Long-distance telegraphy; Ohm's law
- Circuits: graphical representations and mathematical models
- Model and solve very simple (one loop) circuits
- Network Examples: Broadcast Telegraphy, Decorative Lights

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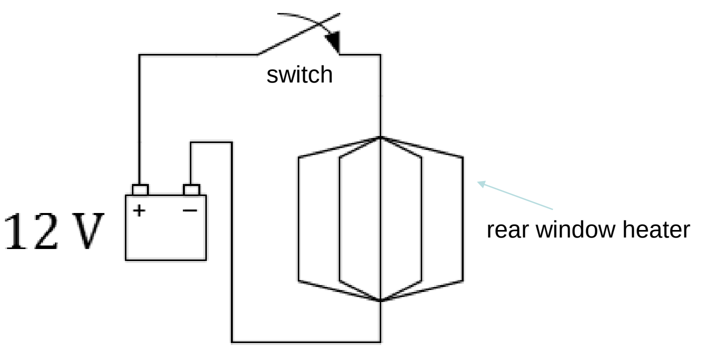
Circuit model for car window defroster

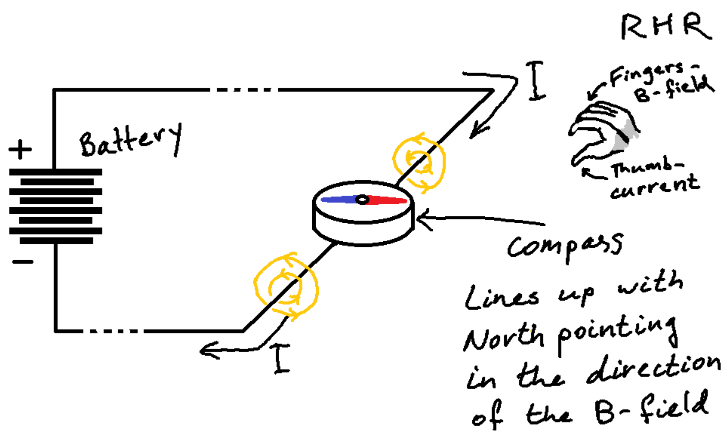
L4Q1: What is the resistance of the car window defroster if it dissipates 60 W? (Consider that the car battery has a max current of 600 A)



L4Q2: What percentage of available battery current is sent to the rear window heater?

A. 1%
B. 10%
C. 50%
D. 75%
E. 95%

Electric current deflects a compass needle



In History…

Hans Christian Oersted's observation of this effect in 1820 surprised him during his lecture demonstration to advanced students. Detailed experiments followed later.

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Galvanometer measures current

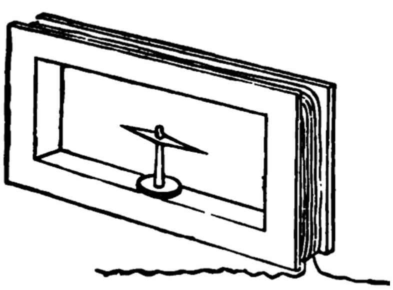
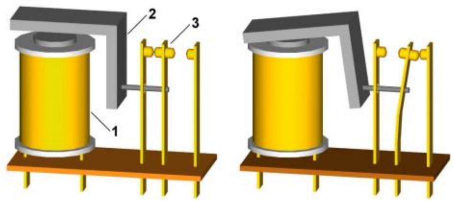


Image from book: Electrical Measurement and the Galvanometer: Its Construction and Uses, by T. D. Lockwood, New York: J. H. Bunnell and Co., 1890 Image in Public Domain.

- Each wire in a coil adds to magnetic field, B
- Wires segments on all sides add to B
- Counteracts Earth's magnetic field
- More current – bigger angle of needle

- More sophisticated galvanometers came later
- Ampere (A), becomes a fundamental unit
- I is for Intensité (Intensity in French)

A coil with current acts as a magnet



Relay principle: 1. Coil, 2. Armature, 3. Moving contact
Source: Wikimedia Commons

L4Q3: For how long can Energizer 522 (~500 mAh) 9 V battery operate a relay (JQX-15F) which draws 100 mA?

Q3 answers:
A. About 1.5 hours
B. About 3 hours
C. About 5 hours
D. About 9 hours
E. About 45 hours

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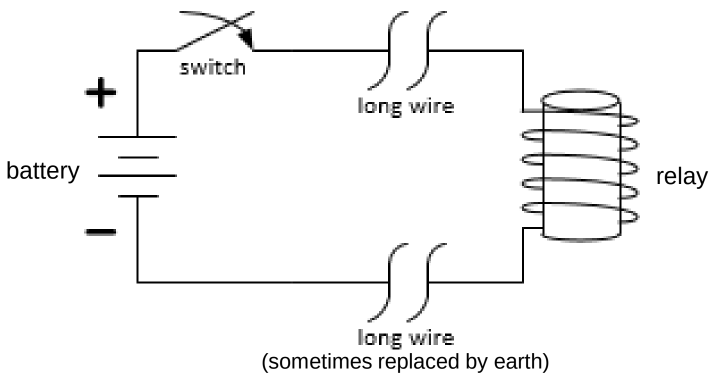
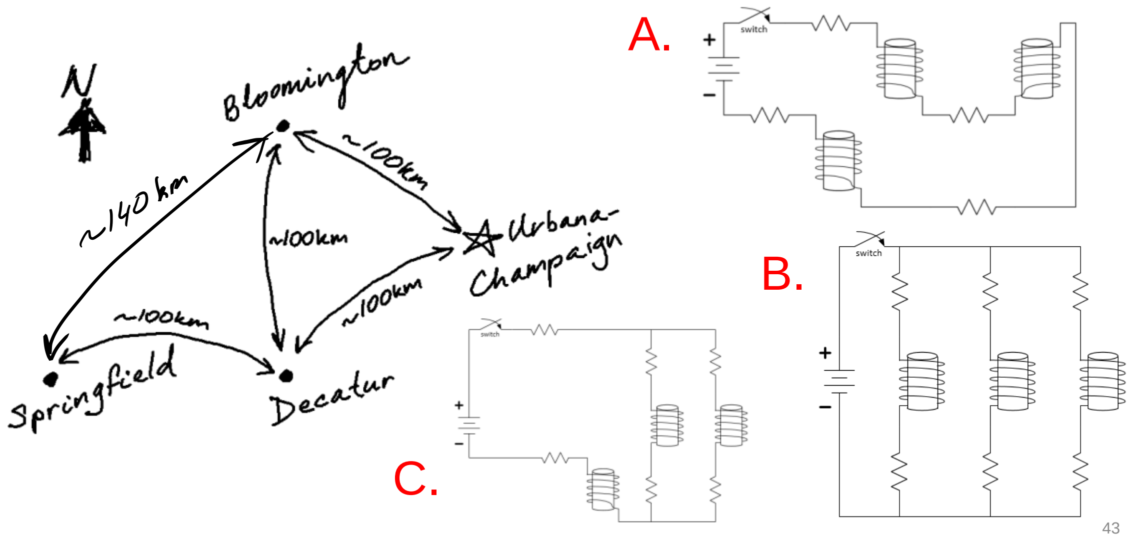
Circuit Model For a Telegraph Loop

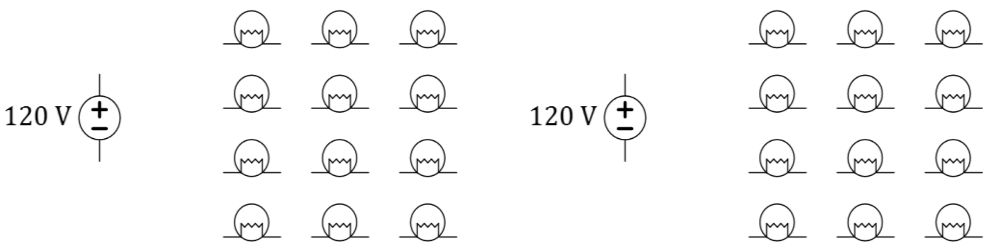


L4Q4: If a 9 V battery with 4 Ω contact resistance is used and the relay has 80 Ω and the wire has 10 Ω/mile, what is the maximum telegraph distance which will result in a 50 mA current through the relay circuit loop?

Broadcasting: multiple ways to wire relays



Decorative lights: multiple ways to connect bulbs to the wall power plug

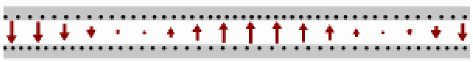


L4Q5: Draw a circuit for 12 lightbulbs connected in *series* in one loop.
L4Q6: Draw a circuit for 12 lightbulbs connected in two *parallel* branches.

L4 Learning Objectives

a. Draw one-loop circuit schematics to model simple setups
b. Draw source and resistor circuits to model real-world problems

Explore More!



ECE 329 Fields and Waves I
ECE 350 Fields and Waves II

A wave traveling rightward along a lossless transmission line.
Black dots represent electrons, and arrows show the electric field.
Image in Public Domain under CC0
Source: https://en.wikipedia.org/wiki/Transmission_line

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ECE110 isn’t my course. It’s *your* course!

- We value your suggestions to make your course better!
- These slides contain only an overview of the course and its materials provided to you. Read the syllabus, course notes, Piazza announcements, and other materials provided at the ECE110 website!
- The University’s Student Code http://admin.illinois.edu/policy/code/ outlines both your rights and responsibilities as a student

Lecture 5: Kirchhoff's Laws in Circuits

- Kirchhoff's Current Law (KCL) – Conservation of Charge
- Kirchhoff's Voltage Law (KVL) – Conservation of Energy
- Solving Circuits with KCL, KVL, and Ohm's Law
- Power Conservation in Circuits

Kirchhoff's Current Law

Current in = Current out

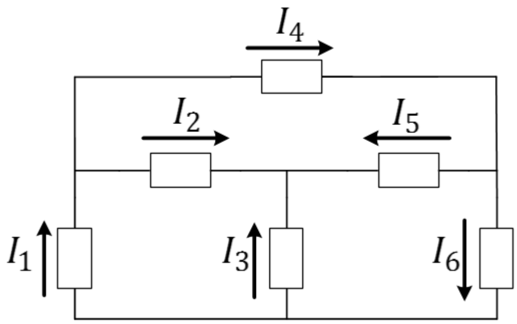
Conservation of charge!

(What goes in must come out, or…
…the total coming in is zero)

Image source: MONGABAY.COM

$$Through\ a\ closed\ surface\ (balloon),\ \sum_{k=1}^{N} I_k = 0\ where\ I_k\ are\ the\ currents\ flowing\ in\ (alt.out)\ of\ the\ balloon.$$

KCL equations are often used at *nodes*, but can also be used for a *sub-circuit*



L5Q1: Which of the equations is NOT a correct application of KCL?

A. $I_1 = I_2 + I_4$
B. $I_4 = I_5 + I_6$
C. $I_1 + I_3 = I_6$
D. $I_3 + I_5 = I_2$
E. $I_6 - I_4 = I_3 + I_2$

Kirchhoff's Voltage Law

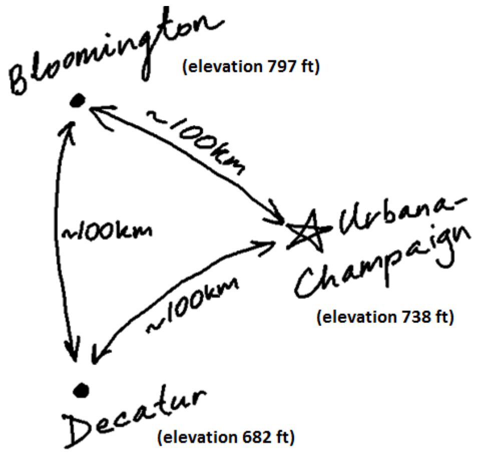
The sum of all voltages around any closed path (loop) in a circuit equals zero

Conservation of Energy!

With voltage, what goes up, must come down

$$\text{Around a closed loop (path)} \sum_{k=1}^{M} V_k = 0 \ \text{ where } V_k \text{ are the voltages measured CW(alt. CCW) in the loop.}$$

KVL and Elevation Analogy



Free Picture: Stairs To The Sky ID: 191634

One can add up elevation changes as we go in a loop from city to city.
The result should be zero, independent of the path taken.

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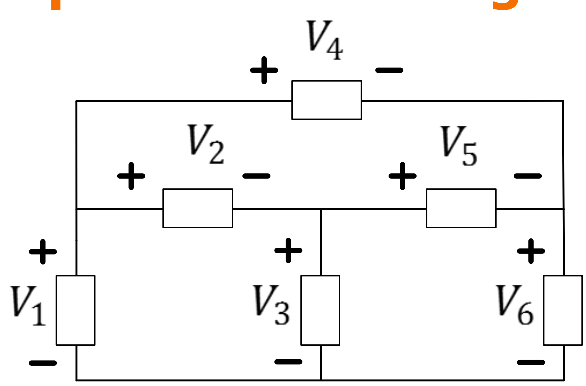
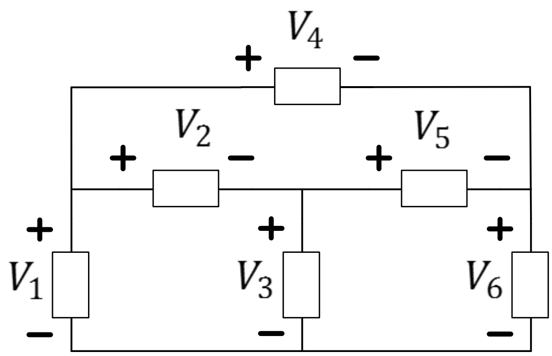
Keeping track of voltage drop *polarity* is important in writing correct KVL equations.



L5Q2: Which of the equations is NOT a correct application of KVL?

A. $V_1 - V_2 - V_3 = 0$
B. $V_1 = V_2 + V_5 + V_6$
C. $V_1 - V_4 = V_6$
D. $V_3 + V_2 = V_1$
E. $V_3 + V_5 = V_6$

Missing voltages can be obtained using KVL.



In History…

The conceptual theories of electricity held by **Georg Ohm** were generalized in **Gustav Kirchhoff**'s laws (1845). Later, **James Clerk Maxwell**'s equations (1861) generalized the work done by Kirchhoff, Ampere, Faraday, and others.

ECE 329 Fields and Waves I

Explore More!

$$\oiint_{\partial\Omega} \mathbf{E}\cdot d\mathbf{S} = \frac{1}{\varepsilon_0}\iiint_{\Omega}\rho\, dV$$

$$\oiint_{\partial\Omega} \mathbf{B}\cdot d\mathbf{S} = 0$$

$$\oint_{\partial\Sigma} \mathbf{E}\cdot d\boldsymbol{\ell} = -\frac{d}{dt}\iint_{\Sigma}\mathbf{B}\cdot d\mathbf{S}$$

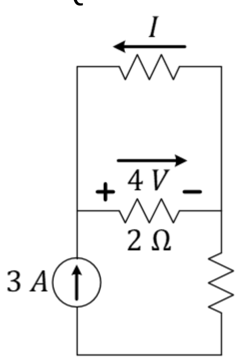
$$\oint_{\partial\Sigma} \mathbf{B}\cdot d\boldsymbol{\ell} = \mu_0\iint_{\Sigma}\mathbf{J}\cdot d\mathbf{S} + \mu_0\varepsilon_0\frac{d}{dt}\iint_{\Sigma}\mathbf{E}\cdot d\mathbf{S}$$

Maxwell's equations in Integral Form
Image Credit: Wikipedia.org

L5Q3: What are the values of the voltages V_1, V_2 and V_6 if $V_3 = 2\,V, V_4 = 6\,V, V_5 = 1\,V$?

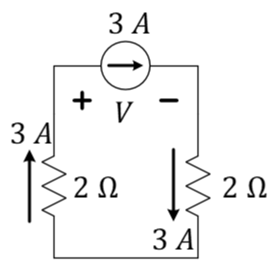
Examples

L5Q4: Find the value of I.



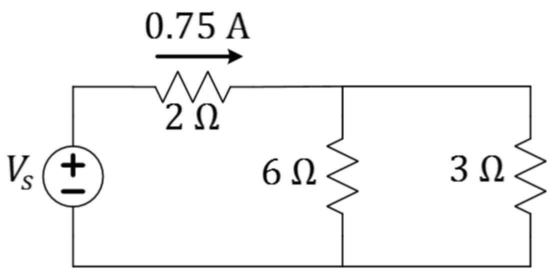
A. $-3\ A$
B. $-2\ A$
C. $-1\ A$
D. $1\ A$
E. $2\ A$

L5Q5: Find the value of V.



A. $-12\ V$
B. $-6\ V$
C. $-3\ V$
D. $6\ V$
E. $12\ V$

Circuits solved with Ohm's + KCL + KVL



L5Q6: What is the value of the source voltage?

L5Q7: How much power is the source supplying?

L5Q8: How much power is each resistance consuming?

L5 Learning Objectives

a. Identify and label circuit nodes; identify circuit loops
b. Write node equation for currents based on KCL
c. Write loop equations for voltages based on KVL
d. Solve simple circuits with KCL, KVL, and Ohm's Law
e. Calculate power in circuit elements, verify conservation

Lecture 6: Current and Voltage Dividers

- Series Connections, Equivalent Resistance, Voltage Divider
- Parallel Connections, Equivalent Resistance, Current Divider
- Power Dissipation in Series and Parallel Resistive Loads
- Example Problems and Practice

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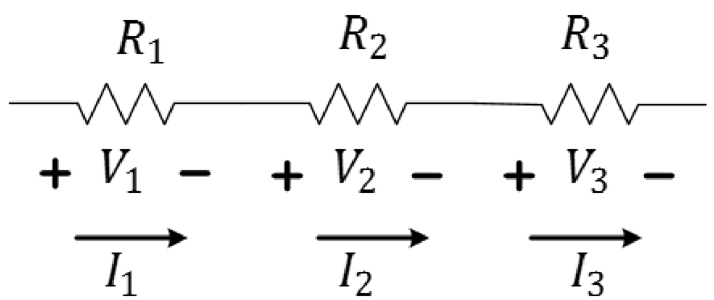
Series Connection

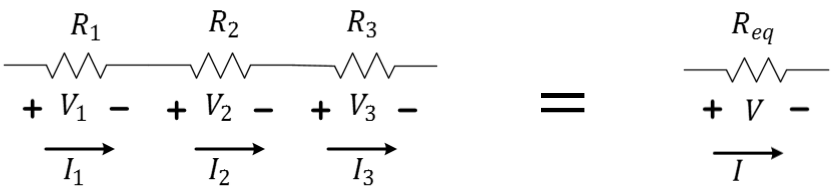
Series connections share the same current



$I_1 = I_2 = I_3$ because of KCL

Equivalent Resistance of Series Resistors

Resistances in series add up



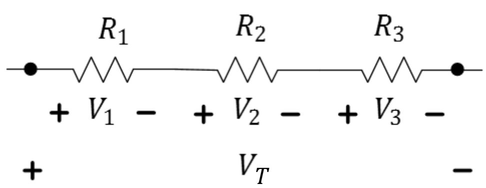
$$R_{eq} = R_1 + R_2 + \cdots + R_N$$

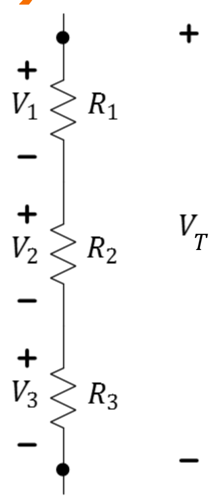
This can be intuitive: think of telegraphy wires in series.

Voltage Divider Rule (VDR)

When a voltage divides across resistors in series, more voltage drop appears across the largest resistor.

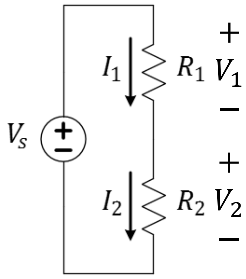
$$V_k = \frac{R_k}{R_{eq}} \cdot V_T$$





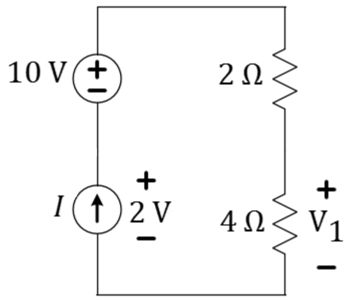
L6Q1: Can a voltage across one of the resistors be higher than the total V_T?

L6Q2: If $R_1 < R_2$, which of the following is true?



A. $V_1 < V_2$ and $I_1 < I_2$
B. $V_1 < V_2$ and $I_1 = I_2$
C. $V_1 = V_2$ and $I_1 = I_2$
D. $V_1 > V_2$ and $I_1 = I_2$
E. $V_1 > V_2$ and $I_1 > I_2$

L6Q3: Use VDR to find V_1.



A. $V_1 \le -6\,V$
B. $-6 < V_1 \le -2\,V$
C. $-2 < V_1 \le 2\,V$
D. $2 < V_1 \le 6\,V$
E. $6\,V < V_1$

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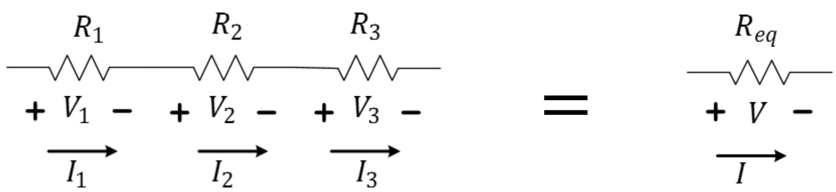
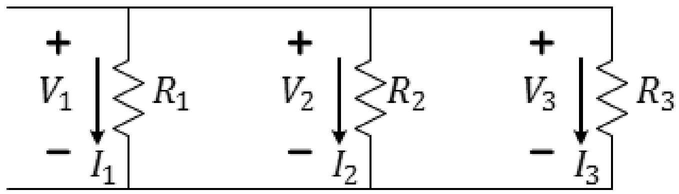
VDR Derivation



Since $I = I_k$, $\frac{V}{R_{eq}} = \frac{V_k}{R_k}$ by Ohm's Law. So, $V_k = \frac{R_k}{R_{eq}} \cdot V$

Parallel Connection

Parallel connections share the same voltage potentials at two end nodes (shared by the elements)



$V_1 = V_2 = V_3$ because of KVL

L6Q4: Are appliances in your house/apartment connected in series (A.) or in parallel (B.)?

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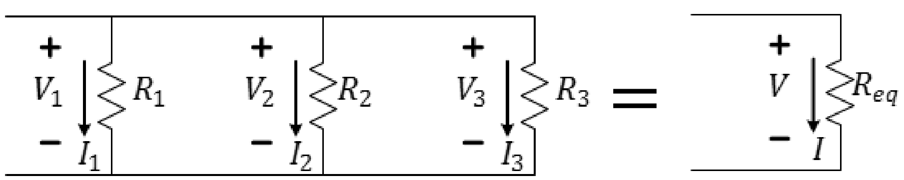
Equivalent Resistance of Parallel Resistors



$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_N}$$

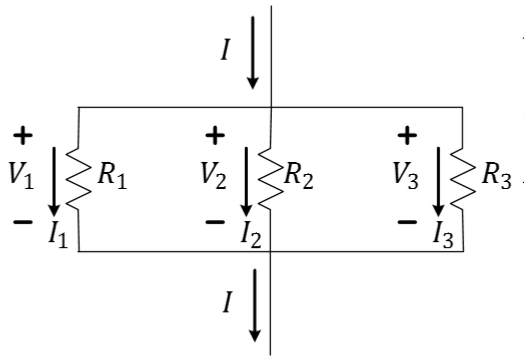
If $N = 2$, $\quad R_{eq} = \frac{R_1 R_2}{R_1 + R_2}$

Adding resistance in parallel always brings resistance down!
This can be intuitive: think of combining wire strands to make a thicker wire.

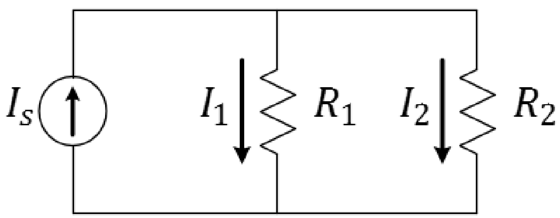
Current Divider Rule (CDR)

When a current divides into two or more paths, more current will go down the path of lowest resistance.

$$I_k = \frac{R_{eq}}{R_k} \cdot I$$



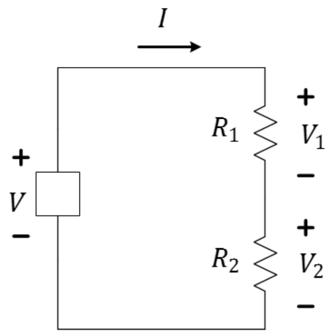
L6Q5: If $R_1 < R_2$, which of the following is true?



A. $I_1 < I_2 < I_s$
B. $I_1 < I_s < I_2$
C. $I_2 < I_1 < I_s$
D. $I_2 < I_s < I_1$
E. $I_s < I_2 < I_1$

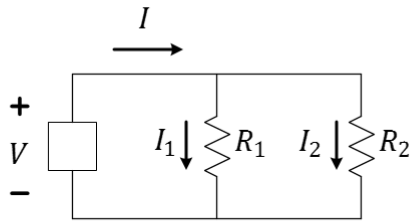
L6Q6: In a parallel connection, does a smaller (A.) or larger (B.) resistor absorb more power?

VDR and CDR for Two Resistances



$$V_1 = \frac{R_1}{R_1 + R_2} V$$

$$V_2 = \frac{R_2}{R_1 + R_2} V$$



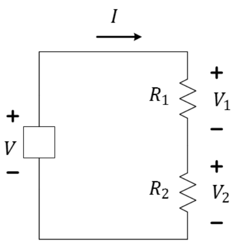
$$I_1 = \frac{R_2}{R_1 + R_2} I \qquad I_2 = \frac{R_1}{R_1 + R_2} I$$

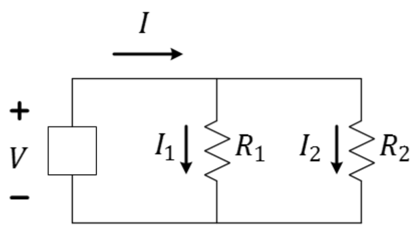
Bad Idea: try to memorize these formulae.
Good Idea: try to note trends and understand concepts !

Example, if $R_1 = 1\ \Omega$ and $R_2 = 2\Omega$, then $V_2 : V_1$ will be in a $2:1$ ratio for the series circuit.
If $R_1 = 1\ \Omega$ and $R_2 = 2\Omega$, then $I_2 : I_1$ will be in a $1:2$ ratio for the series circuit.

Why?

VDR and CDR for Two Resistances

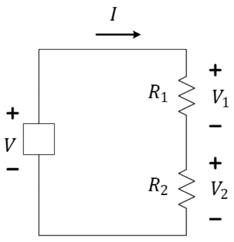


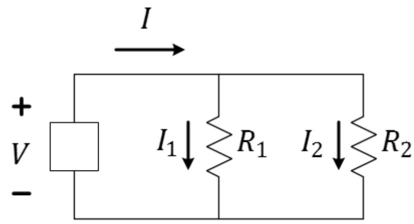


L6Q7: If 6V falls across a series combination of 1kΩ and 2kΩ, what is V across 2kΩ?

L6Q8: If 0.15A flows through a parallel combo of 1kΩ and 2kΩ, what is I through 2kΩ?

VDR and CDR for Two Resistances





L6Q9: If a source supplies 60W to a series combination of 10Ω and 30Ω, what is the power absorbed by the 10Ω resistor? What power is absorbed by the 30Ω resistor?

L6Q10: If a source supplies 300mW to a parallel combination of 3kΩ and 2kΩ, what is the power absorbed by the 3kΩ resistor? What power is absorbed by the 2kΩ resistor?

L6 Learning objectives

a. Identify series and parallel connections within a circuit network
b. Find equivalent resistance of circuit networks
c. Estimate resistance by considering the dominant elements
d. Apply rules for current and voltage division to these networks
e. Apply conservation of energy to components within a circuit network

Lecture 7: More on Sources and Power

- The Meaning of Current and Voltage Sources
- Labeling of Current and Voltage and Sign of Power

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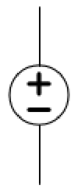
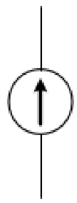
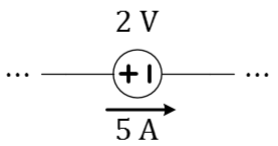
Voltage and Current Sources Can Produce or Consume Power and Energy

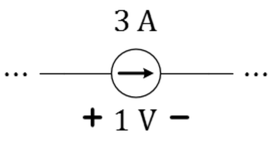
- [Ideal] sources in a circuit are mathematical models
- Can be used to model real devices (or parts of circuit)
- Voltage sources have (calculable) currents through them
- Current sources have (calculable) voltages across them
- Source elements can produce or consume energy





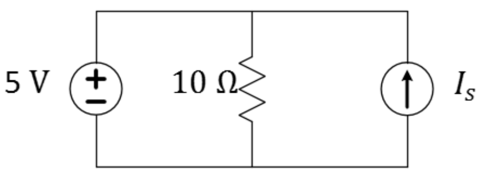
Which of the sources are delivering power?





A. The voltage source only
B. The current source only
C. Both
D. Neither
E. Not enough information to tell

Either or Both Sources Can Supply Power

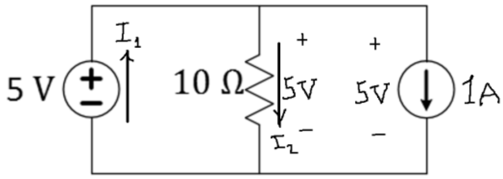


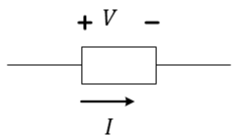
L7Q1: For what values of I_s do both sources supply power?

L7Q2: For what values of I_s does only the current source supply power?

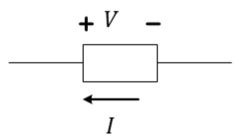
L7Q3: For what values of I_s does only the voltage source supply power?

Claim: Labeling Voltage and Current Polarity Is Arbitrary. When *does* it matter?





"Current downhill" is preferable for resistors



"Current uphill" can be convenient for sources.

If a resistor, then…

$$V = IR$$

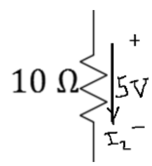
$$V = -IR$$

Answer #1: When applying Ohm's Law,
it is the "downhill current" that equals V over R: $I_{+\to-} = \frac{V}{R}$

Consideration of Polarity Assignments

L7Q4: In what direction does a positive current flow through a resistor?

A. "Downhill" of voltage
B. "Uphill" of voltage
C. Could be either A or B



L7Q5: In what direction does a positive current flow through a battery?

A. "Downhill" of voltage
B. "Uphill" of voltage
C. Could be either A or B

Continued: When *does* polarity assignment matter?

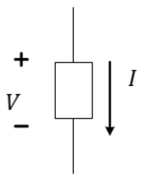
Answer #2: When the sign of power is important.

Recall: power (watts) is energy (joules) divided by time (sec), or volts times current

$$P(t) = V(t)I(t)$$

$$P = VI$$

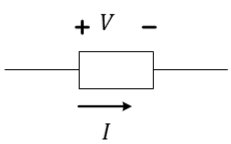
if constant (aka. DC or Direct Current). Using the standard polarity labeling:
$P = \ V_{+-} \ I_{+\to-}$



$P < 0$ $\Rightarrow$ *Element delivers power to the circuit*

$P > 0$ $\Rightarrow$ *Element absorbs power from the circuit*

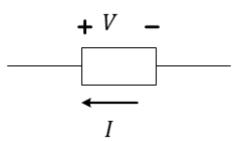
Recap of labeling implication



$$R = \frac{V}{I}$$

$$P = VI$$

"Standard Reference"



$$R = -\frac{V}{I}$$

$$P = -VI$$

"Non-Standard Reference"

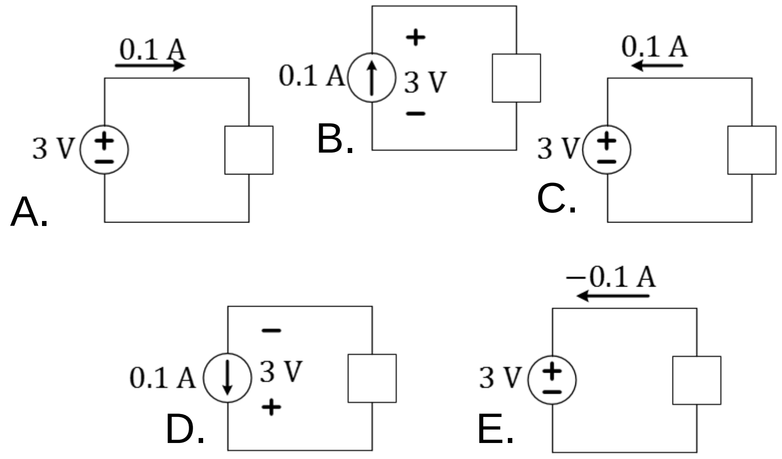
This way, power is defined such that it is negative when it is supplied (sourced) and positive when it is absorbed (sinked).

Universal:

Ohm's Law: $I_{+\to-} = \frac{V}{R}$
Power Eqn: $P = VI_{+\to-}$

L7Q6: With power defined as above,
what is the sum of powers for all circuit elements?

Which of the sources below absorbs power?



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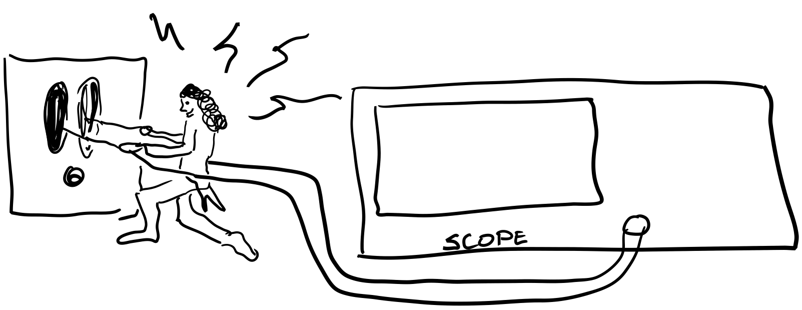
L7 Learning Objectives

a. Use “downhill current” to correctly apply Ohm’s law in a resistor (depending on labeling)
b. Use “downhill current” to determine whether power is absorbed or supplied by an element

Lecture 8: RMS and Power

- Time Varying Voltage Source – Sinusoidal, Square, Etc.
- Root-Means-Square Voltage (RMS) of a Waveform

Voltage from the wall plug is *sinusoidal*



In History…

In the 1880's and 1890's, **Nikola Tesla** played a large role in improving DC motors, developing AC motors and generators, and developing many high-frequency/high-voltage experiments including many in the area of remote control and wireless telephony. **Marconi**'s 1901 cross-Atlantic wireless transmission likely infringed upon a few of Tesla's nearly 300 patents.

L8Q1: What is the peak instantaneous power absorbed by a 250Ω light bulb?

Time Average Power

(similar equation for any time-average)

$$P_{avg} = \frac{AREA_{in\,T}}{T},$$
$$T = period$$

For non-periodic signals (e.g. constant white noise) use

$$T = sufficient\ length\ observation\ interval$$

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Root-Mean-Square averages

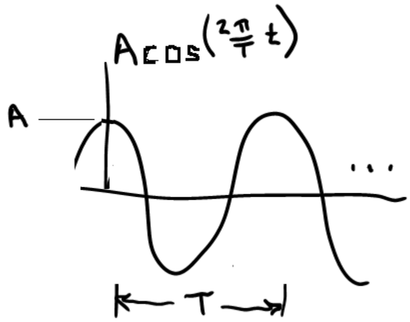
RMS is meaningful when interested in power production/dissipation in AC.

$$V_{RMS} = \sqrt{Average[v^2(t)]}$$

1. Sketch $v^2(t)$
2. Compute $Average[v^2(t)]$
3. Take $\sqrt{\ }$ of the value found in part 2.

Calculating P_{avg} and V_{rms}

$Trig\ identity: \cos(A)\cos(B) = \frac{1}{2}[\cos(A-B)+\cos(A+B)]$

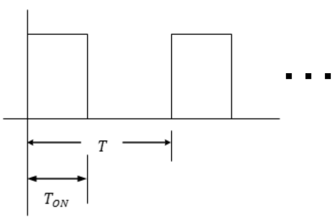


USA "Mains voltage"

L8Q2: What is the average power absorbed by a 250Ω light bulb if A = 170V?

Calculating P_{avg} and V_{rms}

$Duty\ Cycle\ Definition: \quad \frac{T_{ON}}{T}$



L8Q3: What happens to power and V_{rms} when T_{ON} is halved while T is unchanged?

Always remember the fundamental definition of rms

Which equation provides the rms voltage of a PWM signal with a peak voltage of A volts?

A. A
B. $\frac{A}{2}$
C. $\frac{A}{\sqrt{2}}$
D. $\sqrt{Avg\{v^2(t)\}}$ where $v(t)$ is the waveform of the PWM signal.
E. *None of these.*

Remember, you want to learn concepts and not attempt to memorize formulae.

L8 Learning Objectives

a. Compute the time-average power from I(t), V(t) curves
b. Explain the meaning of V_{rms} and relationship to P_{avg}

Lecture 9: IV Characteristics

- Measuring I-V Characteristics of Circuits
- Calculating I-V Characteristics of Linear Circuits
- Operating (I,V) point when Sub-circuits are Connected
- Power and the I-V Characteristics

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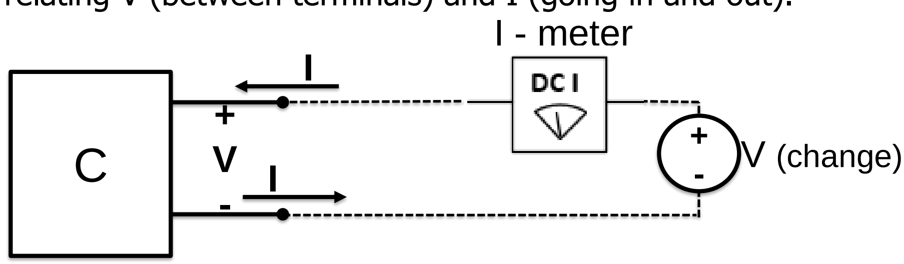
Consider any circuit with two leads

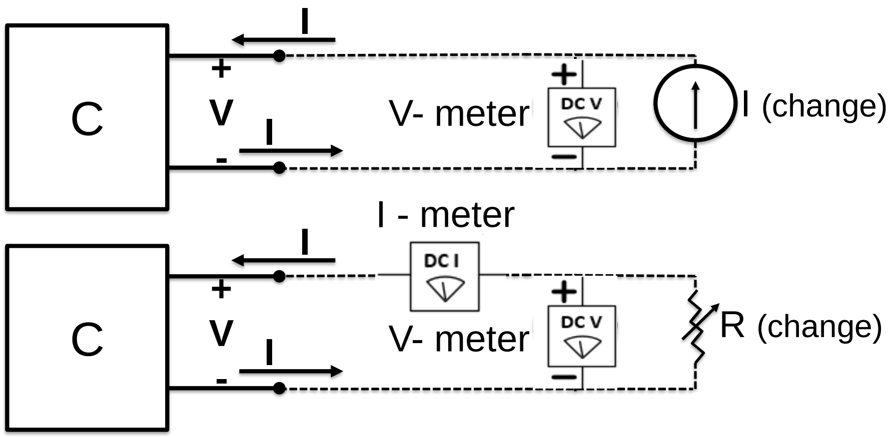
It's DC (not changing in time) behavior can be described by relating V (between terminals) and I (going in and out).



If the circuit is not too close to an ideal voltage source, the IV relationship can be measured like shown above.

L9Q1: What is the voltage drop across an ideal current-meter (ammeter)?

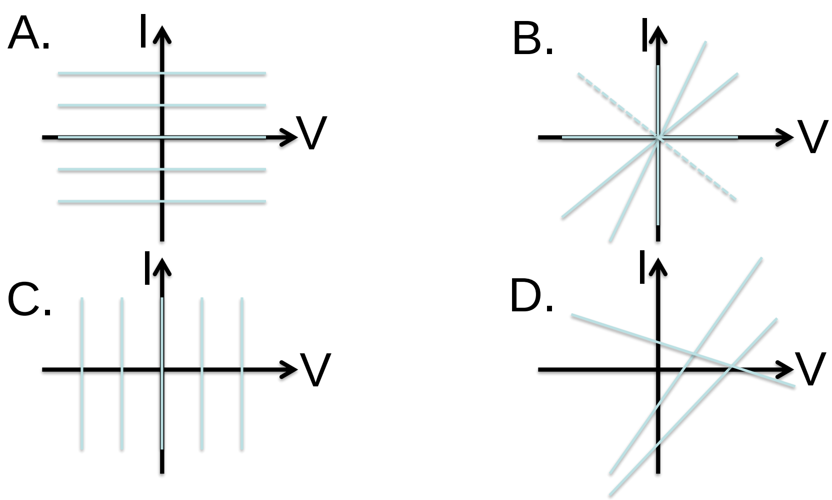
Alternative IV measurements



A variable resistor load is very practical when the circuit C provides power.

L9Q2: What is the current through an ideal voltage-meter (voltmeter)?

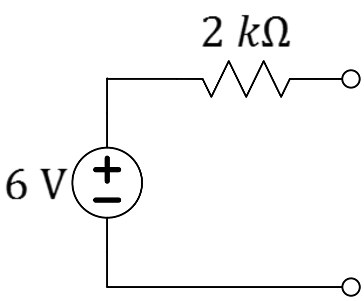
Linear I-V curves

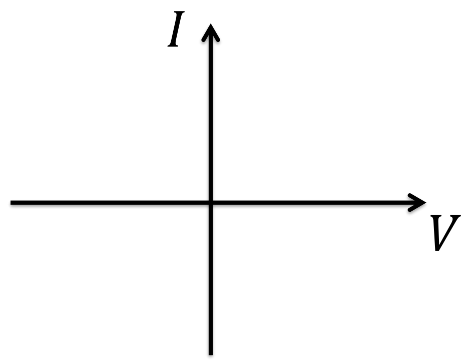


L9Q3: Which set of graphs corresponds to pure resistances?

Simple Series Circuit

Show that the circuit has a linear IV characteristic.





L9Q4: What are the IV characteristics of the circuit above? Include the graph.

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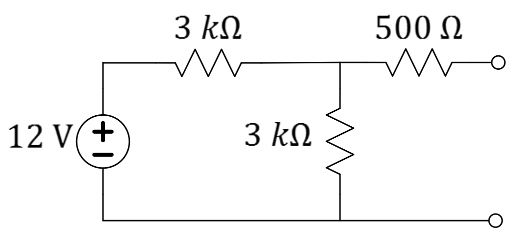
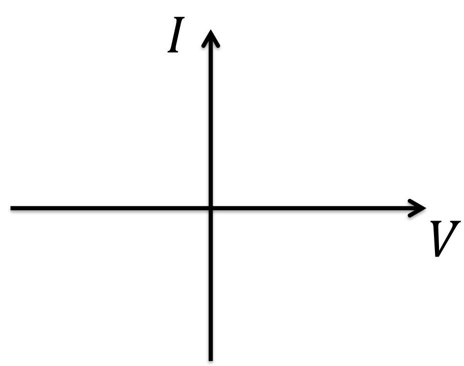
Embedded Voltage Source

Show that this circuit also has a linear IV characteristic.





L9Q5: What are the IV characteristics of the circuit above? Include the graph.

Why we care

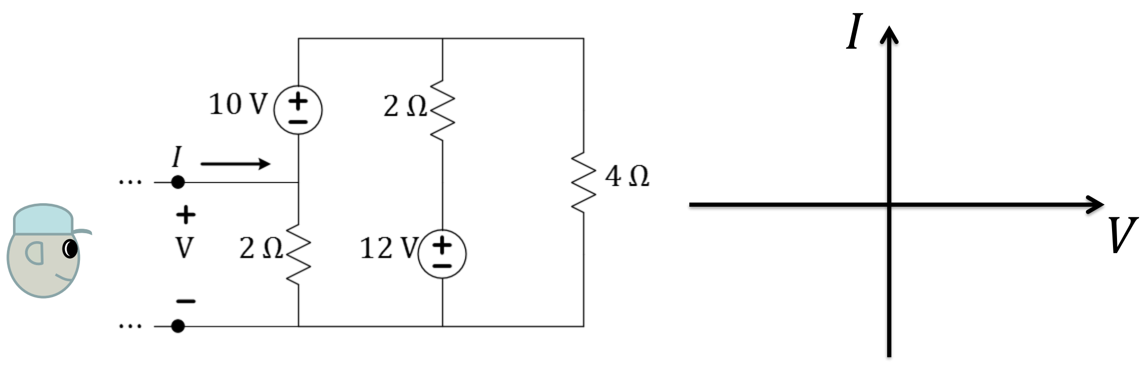
- Allows easy calculation of I and V when two sub-circuits are connected together
- Allows creating a simpler model of a given sub-circuit
- Helps understand nonlinear devices

How to find IV lines

- Use ***circuit analysis*** for *variable* V
- Find two points (usually ***open*** and ***short***)
- Use R_{eff} and either ***open*** or ***short*** (Wednesday)

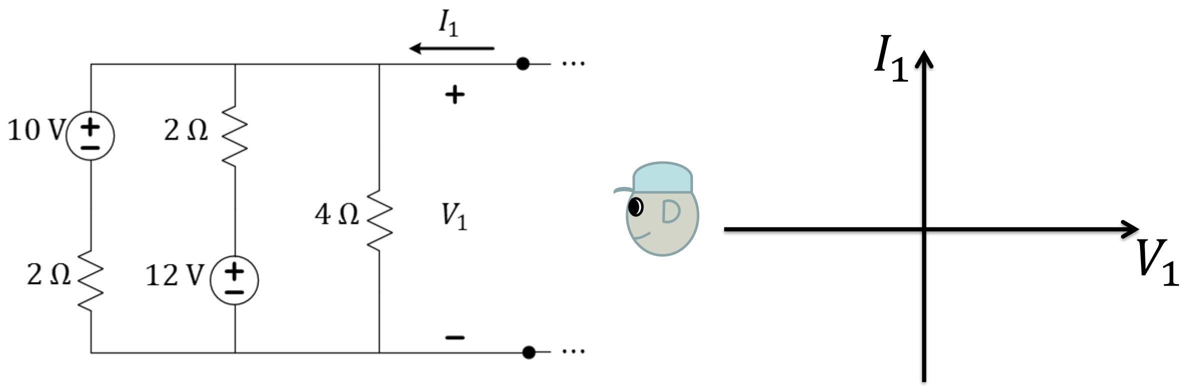
Linear I-Vs of source-resistor circuits

Any combination of current or voltage sources with resistor networks has a linear I-V (between any two nodes).



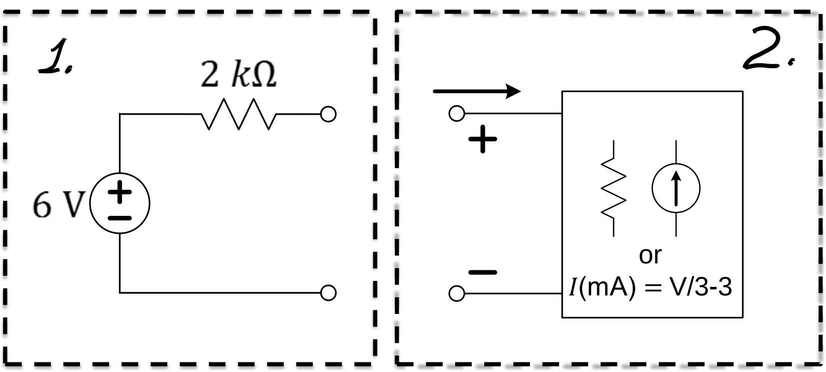
L9Q6: What are the current values I assumes when V is 0V, 2V, 4V?

I-V line for different nodes



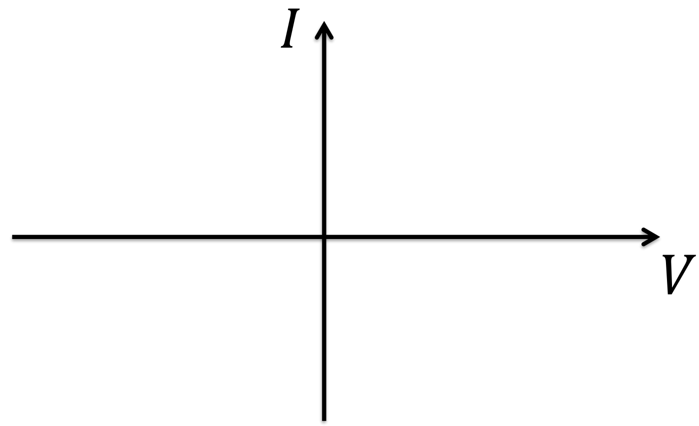
L9Q7: What are the current values taken by I_1 when V_1 is 0V, 2V, 4V?

Connecting two sub-circuits



L9Q8: What are the IV characteristics of a 3 mA current source?
L9Q9: What are the IV characteristics of a 3 kΩ resistor?

Connecting two sub-circuits (cont'd)



L9Q10: Considering the three choices for circuit #2, what is the operating point when the two sub-circuits are connected? Which sub-circuit supplies the power?

L9 Learning Objectives

a. Given one of the three sub-circuit descriptions (IV equation, IV line, diagram), find the other two

   Note that more than one circuit diagram fits an IV description

b. Quickly identify the IV representations of voltage and current sources, resistors, and combinations

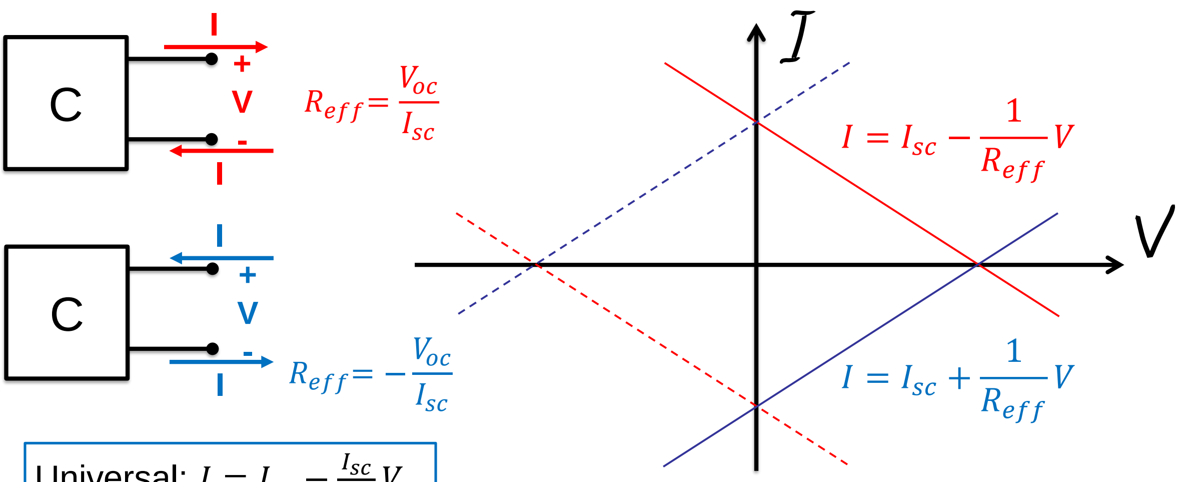
c. Find (V,I) operating points of connected sub-circuits

d. Calculate power flow between connected sub-circuits

Lecture 10: Thevenin and Norton Equivalents

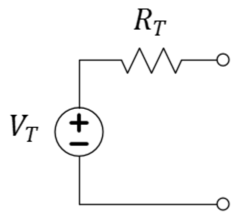
- Review of I-V Linear Equation
- Thevenin and Norton Equivalent Circuits
- Thevenin-Norton Transformation in Circuits
- Calculating R_{eff} by Removing Sources
- Problem Strategy and Practice

Relating I-V Line to Equation

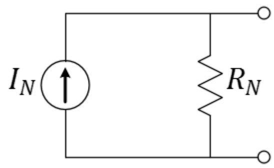


Universal: $I = I_{sc} - \frac{I_{sc}}{V_{oc}} V$

Thevenin and Norton Equivalents

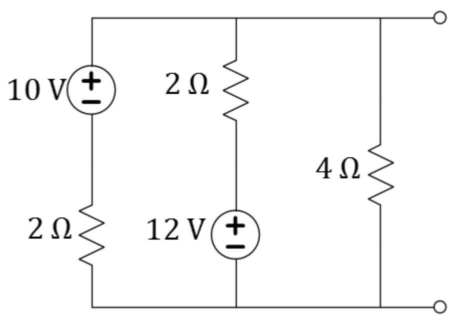


The circuit on the left and the circuit on the right can be made to behave identically by the choice of values as seen through the terminals.



- Either can be used to represent universal: $I = I_{sc} - \frac{I_{sc}}{V_{oc}} V$
- Contain all information on how circuits interact with other circuits
- Loses information on power dissipation WITHIN the circuit

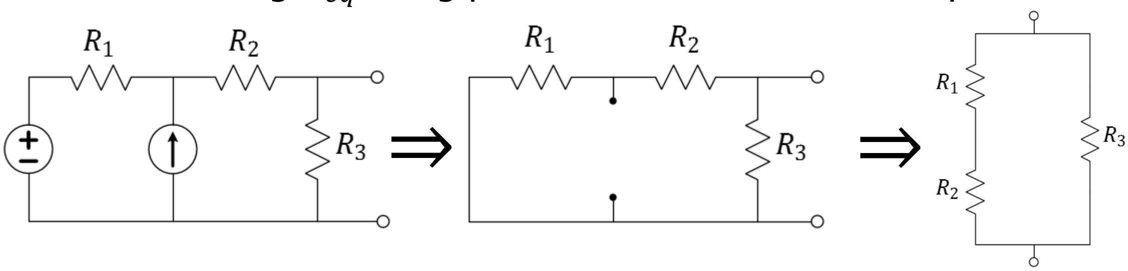
Using Transformation to Find Equivalents



L10Q1: What is the Thevenin equivalent of the circuit above?

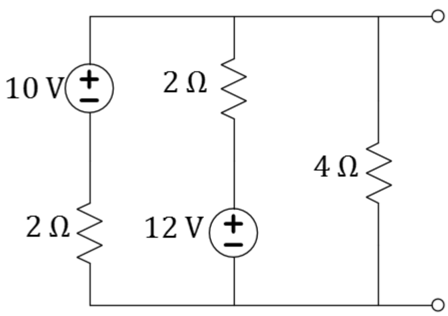
R_{eff} = R_T = R_N is R_{eq} with sources removed

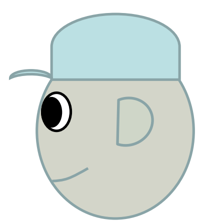
1. Short-circuit all voltage sources (i.e. set them to zero)
2. Open-circuit all current sources (i.e. set them to zero)
3. Find resulting R_{eq} using parallel and series relationships



L10Q2: How is R_{eff} related to the slope of the I-V line?

Finding R_{eff} is easy in multi-source circuits





A. 8 Ω
B. 5 Ω
C. 4 Ω
D. 2 Ω
E. 0.8 Ω

L10Q3: What is R_{eff}, for the circuit above?
L10Q4: Besides R_{eff}, is it easier to find I_{SC} or V_{OC}?

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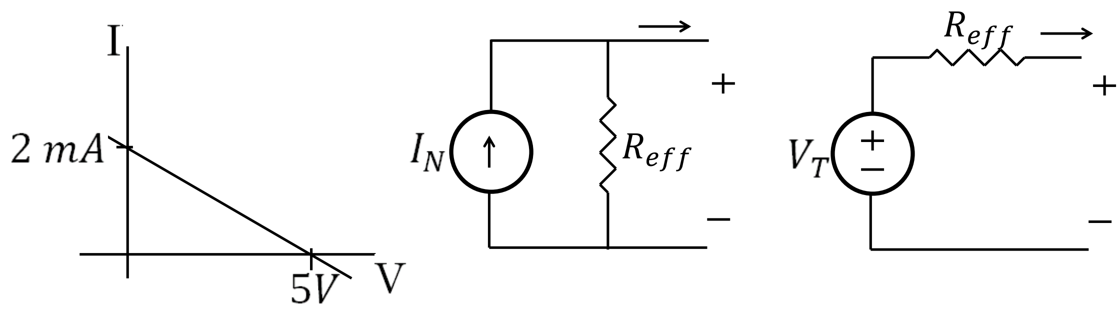
One can find a circuit given a line



L10Q5: What is R_{eff}, for the circuit with the given I-V line?

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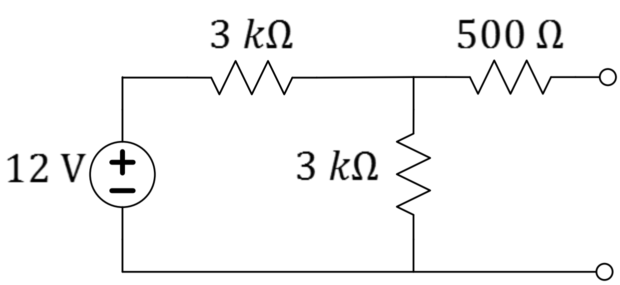
Practice makes perfect!



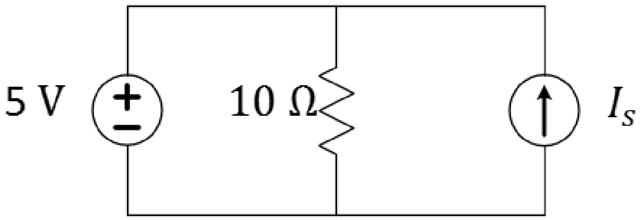
In History…

Leon Charles Thevenin was a telegraph engineer. In 1883, his theorem expanded modelling of circuits and simplified circuit analysis based on Ohm's Law and Kirchhoff's Laws.

The dual "Norton's theorem" didn't arrive until 1926 with the efforts of Bell Labs engineer, **Edward Lawry Norton**.

L10Q6: What are the Thevenin and Norton equivalents for the circuit above?

Flashback! Use Thevenin to solve.



Q7: For what values of I_s does only the voltage source supply power?

Summary

- Any linear network can be represented by a simple series Thévenin circuit or, equivalently, by a simple parallel Norton circuit
- There are several methods for determining the quantities and depending on what is given about the original circuit
- It is the same resistance, R_{eff}, value for both the Thévenin and the Norton circuits, found as R_{eq} with the sources removed (SC for V-sources, OC for I-sources)

L10 Learning Objectives

a. Represent *any* (non-horizontal) linear IV characteristic by a series combination of a voltage source and a resistor (Thévenin equivalent circuit).

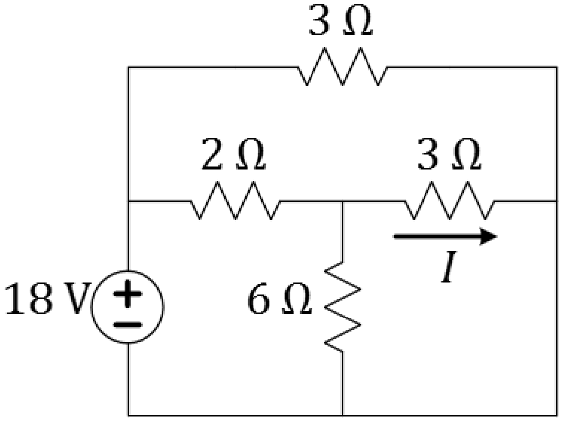
b. Represent *any* (non-vertical) linear IV characteristic by a parallel combination of a current source and a resistor (Norton equivalent circuit).

c. Find the parameters of Thévenin and Norton equivalent circuits, $R_{eff}, V_T,$ and I_N when given a circuit.

Lecture 11: Node Method For Circuit Analysis

- Review of circuit-solving strategies
- Node Method steps
- Practice with the Node Method

What are the possible strategies to find *I*?

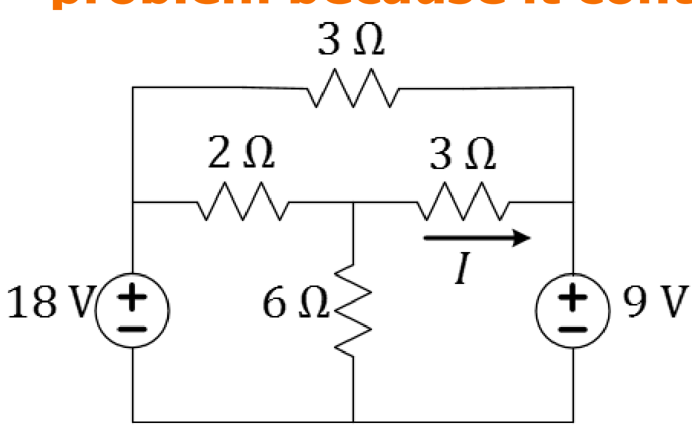


L11Q1: Is one of the resistors in parallel with the voltage source? If so, which?
L11Q2: What is the value of the labeled current?

The Node Method

1. Identify or pick "ground" (0 V reference)
2. Label all the node voltages
   (use values when you can; variables when you must)
3. Use KCL at convenient node(s)/supernode(s)
4. Use voltages to find the currents

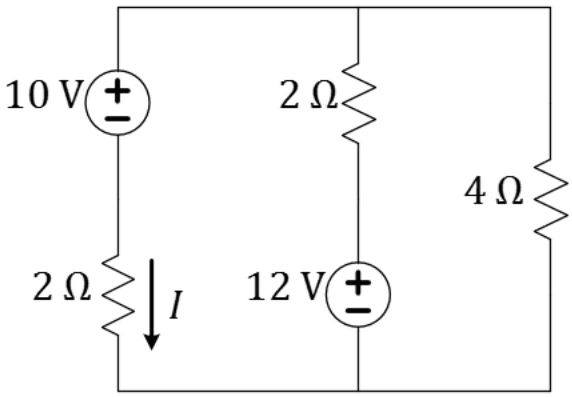
Node method is a good strategy for this problem because it contains two sources



A. 1
B. 2
C. 3
D. 4
E. 5

L11Q3: How many nodes are in the circuit?
L11Q4: What is the value of the labeled current?

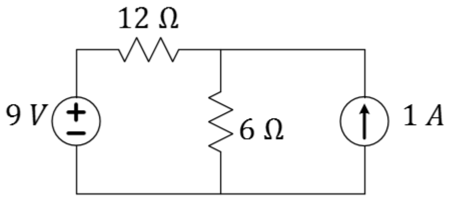
A *floating* voltage source: relates two nodes but has no known relationship to ground



A. 1
B. 2
C. 3
D. 4
E. 5

L11Q5: How many nodes are in the circuit?
L11Q6: What is the value of the labeled current?

Voltage across a current source is unknown



L11Q7: What is the power supplied or consumed by each element?

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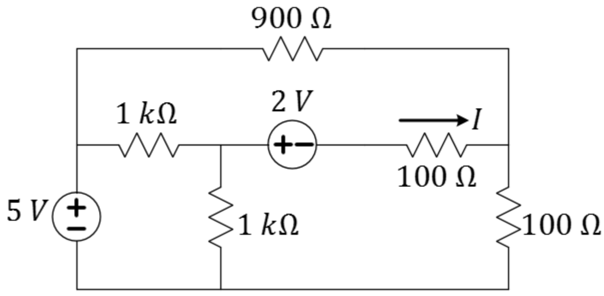
Sometimes two or more node voltages are unknown (more challenging!)



L11Q8: What is the value of *I* in the circuit above?

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L11 Learning Objectives

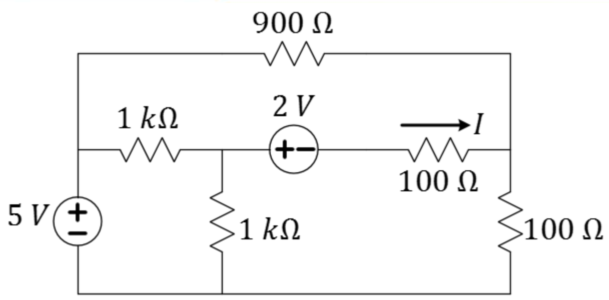
a. Outline (list, describe) steps of the Node Method

b. Use these steps to speed the process of performing circuit analysis via KCL/KVL/Ohm's

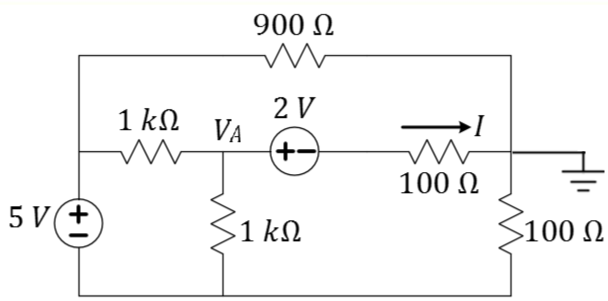
c. Identify circuit patterns in which different techniques might simplify the process of finding a solution (Practice!)

Lecture 12: Exercises

- We will use this lecture to catch up, if needed
- We will also do more exercises on recent topics
- Slides may be distributed in lecture



L12Q1: What is the value of *I* in the circuit above?



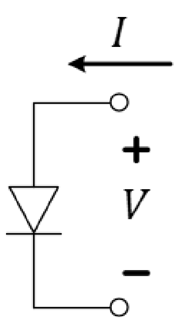
L12Q2: What is the value of V_A in the circuit above?

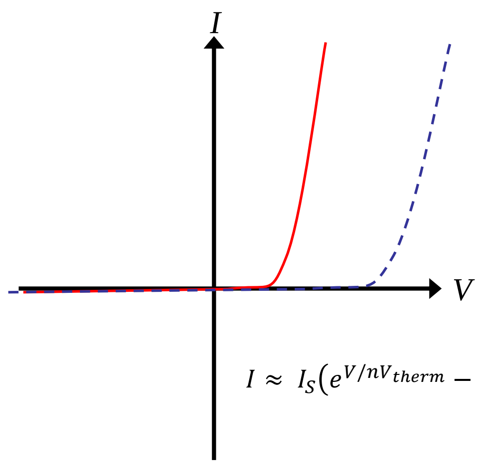
Lecture 13: Introduction to Diodes

- Diode IV characteristics
- Connecting diode to a linear circuit
- Piecewise linear models of diodes

Recommended: https://learn.sparkfun.com/tutorials/diodes

Diode as a two-terminal device





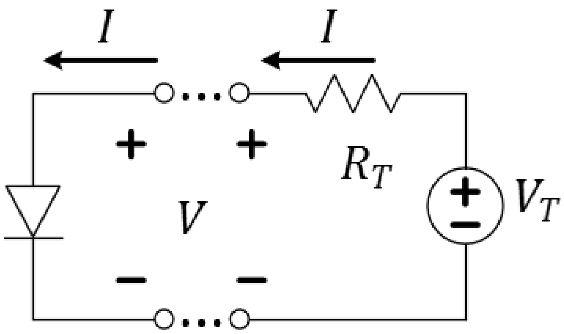
$I \approx I_S\left(e^{V/nV_{therm}} - 1\right)$

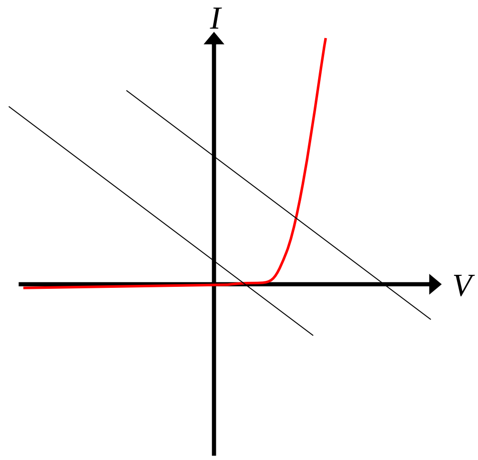
Made out of *semiconductor* materials like Si, Ge, AlGaAs, GaN with some additives called *dopants.*

Major applications: lighting, electronics

L13Q1: Based on the exponential equation for IV, can the diode supply power?

Connecting diode to a linear circuit



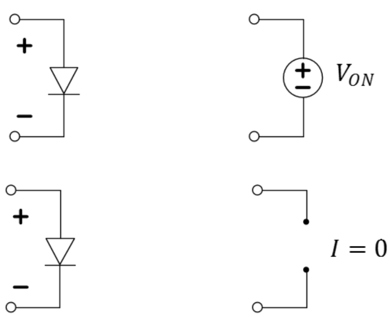


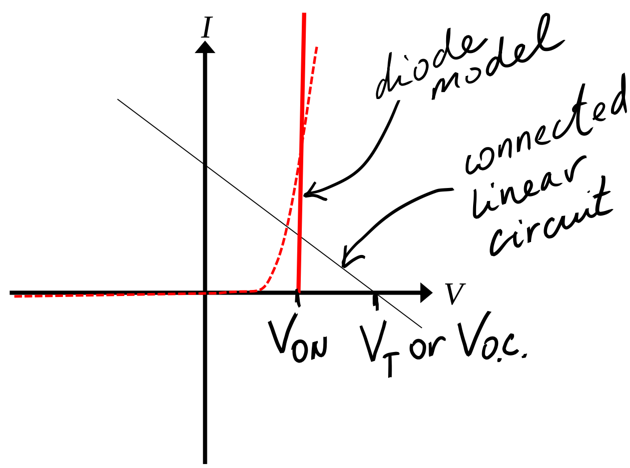
We can solve graphically for an operating point.
For an LED more current means more light.

L13Q2: What is the current flowing through the diode if $V_T < 0$?

Modeling diode with linear IV segments

Instead of looking for graphical solutions, we can approximate the diode with two line segments, corresponding to diode's regimes of operation.





L13Q3: What is the minimum V_T of the connected linear circuit which causes current to flow through the diode if the piecewise linear model above is used?

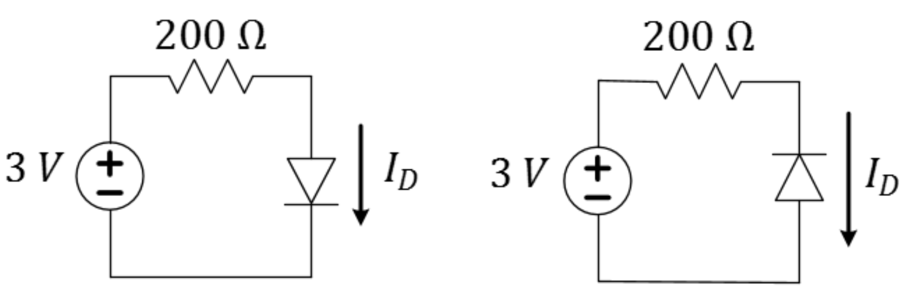
Different diode types have different V_{ON}

Diode Type	V_{ON}(V)	Applications
Silicon	0.6-0.7	General; integrated circuits; switching, circuit protection, logic, rectification, etc.
Germanium	~0.3	Low-power, RF signal detectors
Schottky	0.15-0.4	Power-sensitive, high-speed switching, RF
Red LED (GaAs)	~2	Indicators, signs, color-changing lighting
Blue LED (GaN)	~3	Lighting, flashlights, indicators
"Ideal"	0	Can neglect V_{ON} for high voltage applications

Q4:
A. $3\ mW$
B. $9\ mW$
C. $30\ mW$
D. $90\ mW$
E. $900\ mW$

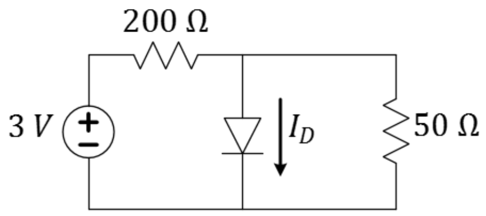
L13Q4: What is the power dissipated by a Ge diode if 30 mA is flowing through it?

Diode circuit examples (offset ideal model)



Assume offset-ideal model with V_{ON} = 0.7 (common Si diodes)
L13Q5: What is the current through the diode in the top left circuit?
L13Q6: What is the current through the diode in the top right circuit?

Diode circuit examples (offset ideal model)



Assume offset-ideal model with V_{ON} = 0.7 (common Si diodes)

L13Q7: What is the current through the diode in the circuit?

$I_D =$

A. $-11.5\ mA$
B. $-2.5\ mA$
C. $0\ mA$
D. $+2.5\ mA$
E. $+11.5\ mA$

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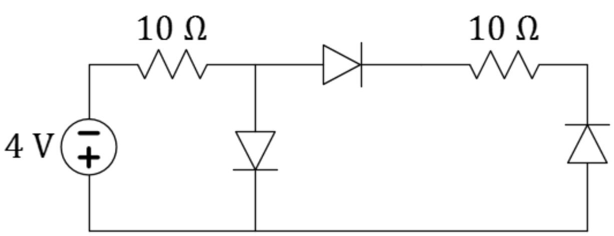
Back-to-back diodes in series are modeled by OIM as an open circuit



L13Q8: Assume OIM with V_{ON} = 0.7 V (Si) What is the current through the left-most diode?

A. 0 *Amps*
B. 0.2 *Amps*
C. 0.33 *Amps*
D. 0.4 *Amps*
E. 3.3 *Amps*

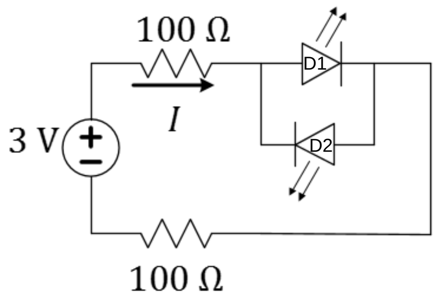
L13 Learning Objectives

a. Draw a "typical" diode IV curve and describe its shape
b. Explain how to use graphical analysis to find the operating point of a diode connected to a linear circuit
c. Describe the offset ideal diode model (open, V-source)
d. Solve simple circuit problems with one diode, given V_{ON}

Lecture 14: Diode Circuits

- Guess-and-check for diode circuits
- Current-limiting resistors and power dissipation
- Voltage-limiting (clipping) diode circuits

Guess-and-check example



Assume OIM with V_{ON} = 2 V (red LED)

L14Q1: What is the current supplied by the voltage source?

L14Q2: What is the power dissipated in each diode?

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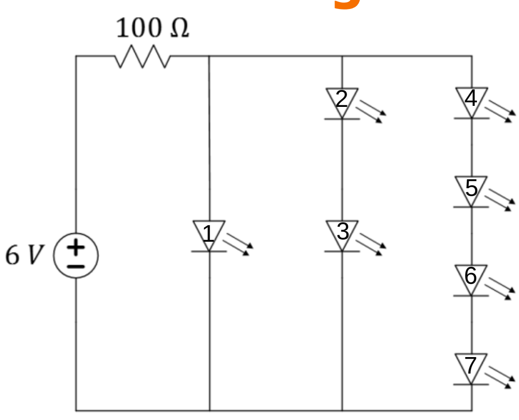
Another guess-and-check example

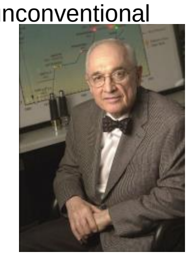


$V_{on} = 2\,V$

Q3:
A. 1
B. 3
C. 4
D. 7
E. *other*

ECE Spotlight…

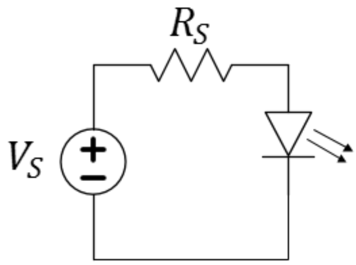
The first visible-light LED was developed by University of Illinois alumnus (and, later, professor) Nick Holonyak, Jr., while working at General Electric in 1962 with unconventional semiconductor materials.
He immediately predicted the widespread application of LED lighting in use today.



L14Q3: How many red LEDs are turned on in the circuit above? (Use OIM)

Current-limiting resistors for LEDs

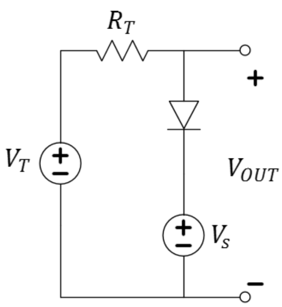
Assume OIM with V_{ON} = 3.3 V (blue LED)

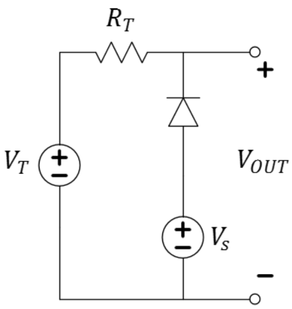


L14Q4: How many 1.5 V batteries are needed to turn on the LED?
L14Q5: What is the series resistance needed to get 16 mA through the LED?
L14Q6: What is the resulting power dissipation in the diode?

Setting voltage limits with diodes

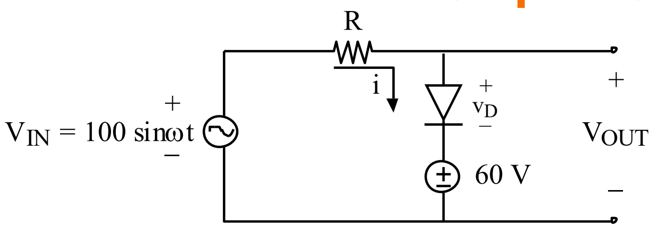
Assume OIM model with V_{ON} = 0.3 V (Ge diode)





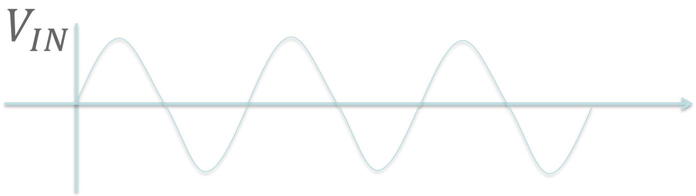
L14Q7: What is the possible range of the output voltages in the left circuit?
L14Q8: What is the possible range of the output voltages in the right circuit?

A voltage-clipping circuit sets maximum or minimum output voltage



KVL:

$V_{OUT} = 60 + v_D$



L14Q9: If the input voltage waveform is shown, what is the output waveform, assuming an ideal diode model (V_{ON} = 0 V)?

L14 Learning Objectives

a. Solve circuit analysis problems involving sources, resistances, and diodes
b. Estimate power dissipation in diode circuits
c. Select appropriate current-limiting resistors
d. Determine voltage limits and waveforms at outputs of diode voltage-clipping circuits

Lecture 15: Exercises, Start Lecture 16!

- We will use this lecture to catch up, if needed
- We will do multiple exercises
- Slides may be distributed in lecture

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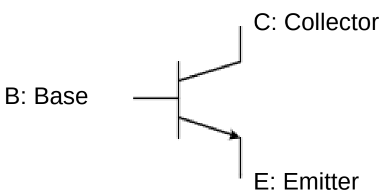
L16: The Bipolar Junction Transistor (BJT)

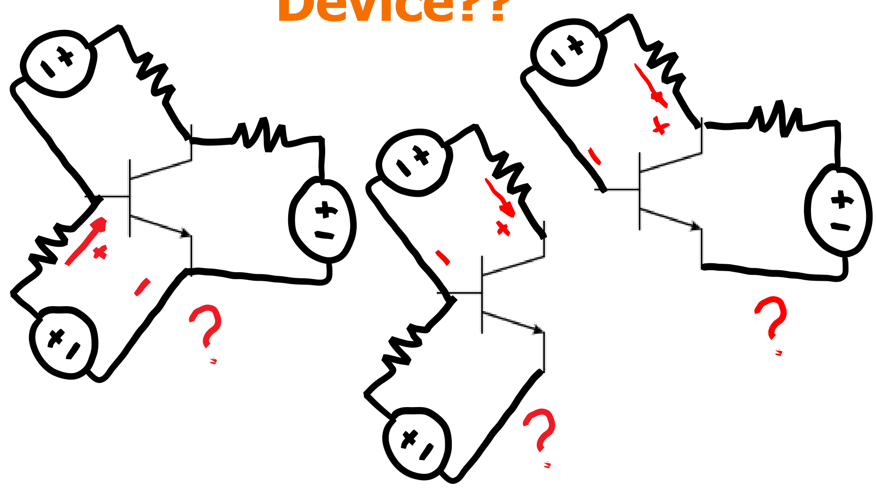
- BJT is a controlled current source…
  - current amplifier
- The three operating regimes of a BJT
- Controlling a resistive load with a BJT
- Solving for saturation condition



ECE Spotlight…

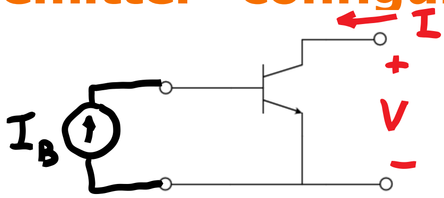
John Bardeen, the co-inventer of the transistor, was also the Ph.D. advisor at the University of Illinois for Nick Holonyak, Jr. of LED fame.

IV Characteristic of a 3-terminal Device??



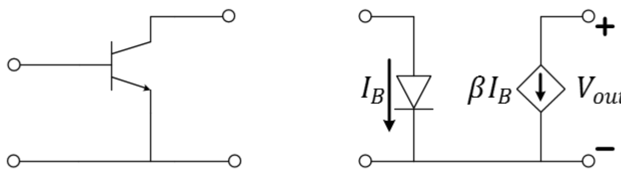
No single way to connect three-terminal device to a linear circuit.

ECE110 considers only the "common-emitter" configuration



If we fix I_B, we can measure the resulting I and V at the other side.

The BJT's "common-emitter NPN" model



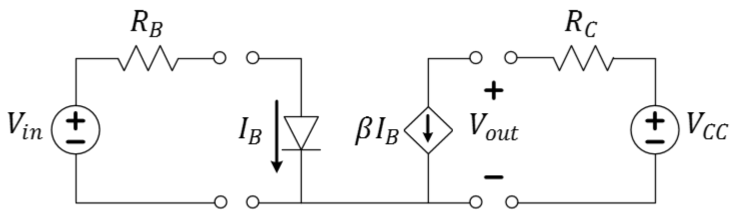
Constraints:

- Limited current range: $\beta I_B \geq 0$
- Limited voltage range: $V_{out} > 0$

L16Q1: Given these constraints, can this "dependent" current source deliver power?

A. Yes, all current sources can supply power
B. No, this current source cannot supply power
C. Neither A or B is correct.

Two Loops Coupled by Current Equation



Constraints:

- Limited current range: $0 \leq \beta I_B \leq I_{max}$ (implied by V_{min})
- Limited voltage range: $V_{out} \geq V_{min} \approx 0$

L16Q2: Right-side KVL: Find an equation relating I_{max} to V_{min}.

L16Q3: Left-side KVL: Find the smallest V_{in} such that $I_B > 0$ (if $\mathrm{V_{on}} = 0.7\ V$)?

L16Q4: What is I_B if $V_{in} = 3\ V$ and $R_B = 4.6\ k\Omega$?

L16Q5: Let $V_{CC} = 6\ V, R_C = 580\ \Omega, V_{min} = 0.2\ V, \beta = 100$. What is I_C under the same input settings as the previous question?

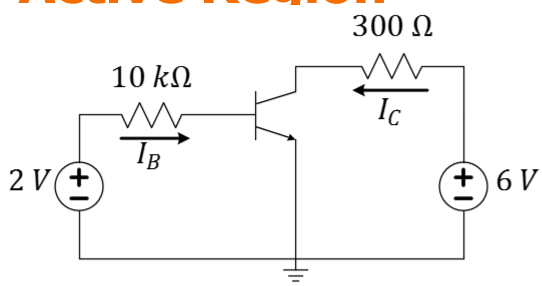
BJT Datasheet Parameters 2N5192G

ELECTRICAL CHARACTERISTICS* ($T_C = 25°C$ unless otherwise noted)

	Characteristic	Symbol	Min	Max	Unit
	ON CHARACTERISTICS (Note 1)				
$\approx \beta$	DC Current Gain ($I_C = 1.5$ Adc, $V_{CE} = 2.0$ Vdc) 2N5190G/2N5191G 2N5192G ($I_C = 4.0$ Adc, $V_{CE} = 2.0$ Vdc) 2N5190G/2N5191G 2N5192G	h_{FE}	 25 20 10 7.0	 100 80 – –	–
$V_{CE,sat}$	Collector–Emitter Saturation Voltage ($I_C = 1.5$ Adc, $I_B = 0.15$ Adc) ($I_C = 4.0$ Adc, $I_B = 1.0$ Adc)	$V_{CE(sat)}$	 – –	 0.6 1.4	Vdc
$V_{BE,on} \leq$	Base–Emitter On Voltage ($I_C = 1.5$ Adc, $V_{CE} = 2.0$ Vdc)	$V_{BE(on)}$	–	1.2	Vdc

L16Q6: Approximate the values of β, V_{BEon}, and $V_{CE,sat}$ from the datasheet.

BJT in Active Region



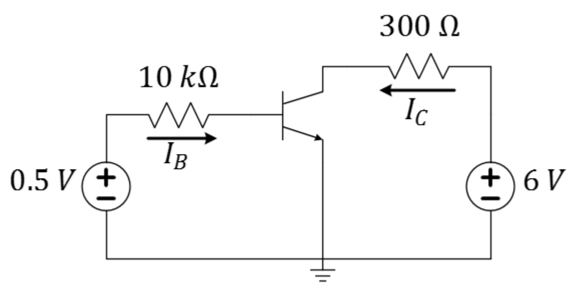
BJT datasheet parameters:

- $\beta = 100$
- $V_{BE,on} = 1\ V$
- $V_{CE,sat} = 0.2\ V$

L16Q7: Find I_B.
L16Q8: Find I_C.

Q7:
A. $I_B = 0\ \mu A$
B. $I_B = 1\ \mu A$
C. $I_B = 2\ \mu A$
D. $I_B = 10\ \mu A$
E. $I_B = 100\ \mu A$

BJT in Cutoff



BJT datasheet parameters:

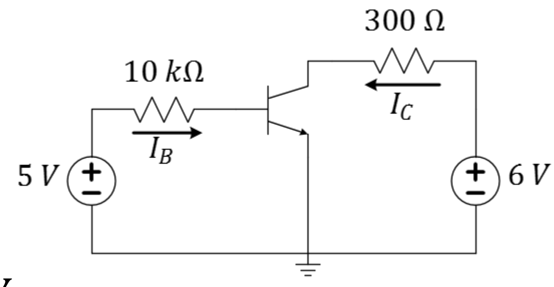
- $\beta = 100$
- $V_{BE,on} = 1\ V$
- $V_{CE,sat} = 0.2\ V$

L16Q9: Find I_B.
L16Q10: Find I_C.

BJT in Saturation

BJT datasheet parameters:

- $\beta = 100$
- $V_{BE,on} = 1\ V$
- $V_{CE,sat} = 0.2\ V$

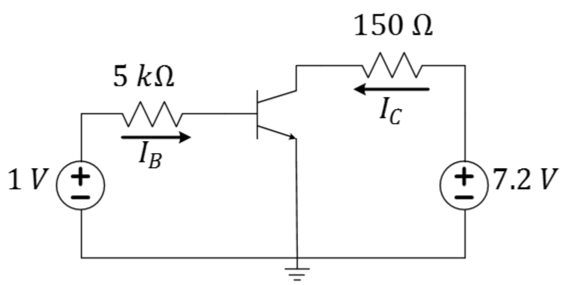


L16Q11: Find I_B.
L16Q12: Find I_C.

BJT Exercise

BJT datasheet parameters:

- $\beta = 100$
- $V_{BE,on} = 1\ V$
- $V_{CE,sat} = 0.2\ v$

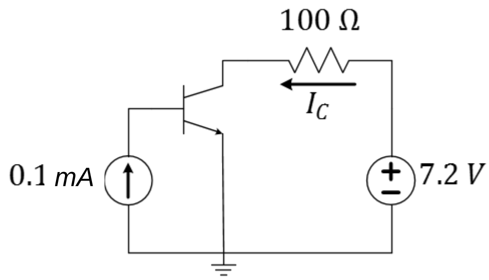


L16Q13: Find I_C and identify in which regime the transistor is operating.

BJT Exercise

BJT datasheet parameters:

- $\beta = 100$
- $V_{BE,on} = 1\ V$
- $V_{CE,sat} = 0.2\ V$



L16Q14: Find I_C and identify in which regime the transistor is operating.
L16Q15: Determine the power consumed by the transistor.

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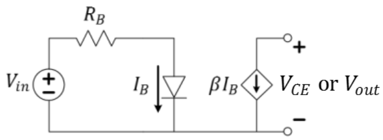
L16 Learning Objectives

a. Identify B, E, C terminals on an npn-BJT symbol
b. Explain BJT's three regimes of operation
c. Calculate active-regime I_C using V_{BEon} in the BE loop
d. Calculate maximum I_C based on $V_{CE,sat}$ and CE loop
e. Calculate I_C given complete biasing conditions and transistor parameters, no matter which regime
f. Calculate the power dissipated by a transistor

Lecture 17: BJT IV Characteristics

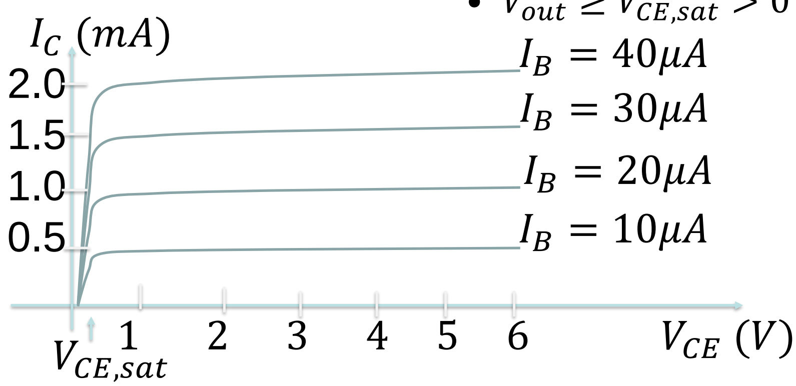
- Interpreting CE junction IV curves for transistor parameters
- Interpreting load line IV curves
- Analysis of IV curves for the (I,V) operating point
- Explore the saturation condition
- Solving transistor-regime problems

BJT IV curves of the CE junction



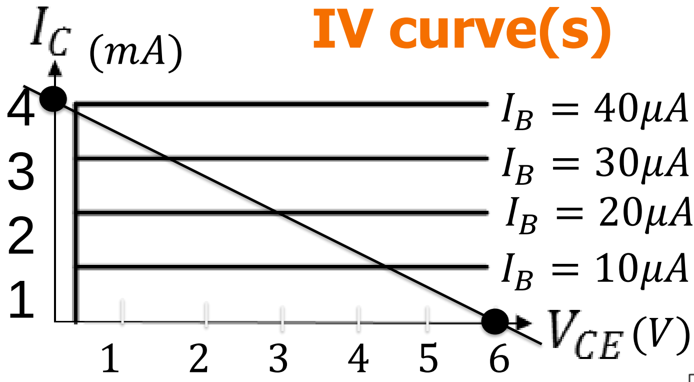
Constraints:

- $0 \le \beta I_B \le I_{C,sat}$
- $V_{out} \ge V_{CE,sat} > 0$



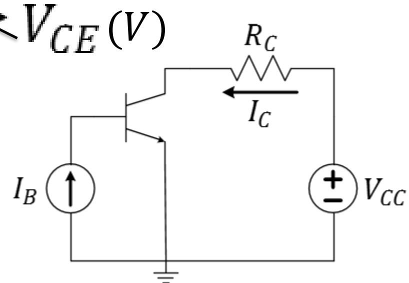
L17Q1: Use the IV plots above to estimate the value of β.

Extracting information from the IV curve(s)



Q6:

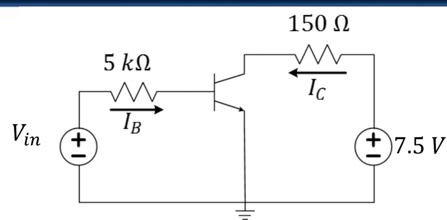
A. $I_B = 40\mu A$
B. $I_B = 30\mu A$
C. $I_B = 20\mu A$
D. $I_B = 10\mu A$
E. $I_B = 0\mu A$

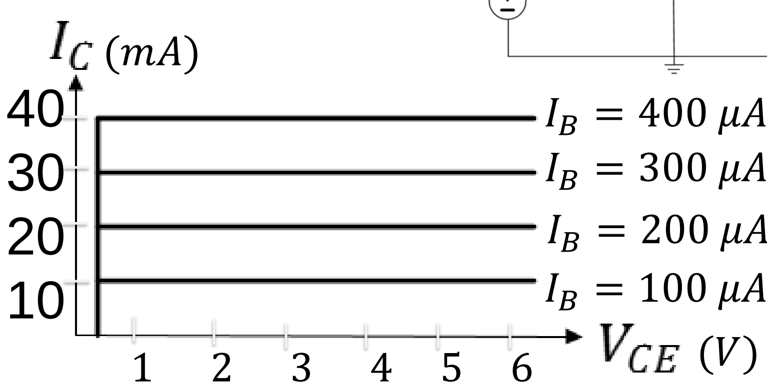


L17Q2: What is β and $V_{CE,sat}$?
L17Q3: What is V_{CC}?
L17Q4: What is R_C?
L17Q5: What is $I_{C,sat}$?
L17Q6: Which I_B results in saturation?

BJT Exercise

$V_{BE,on} = 0.7\ V$

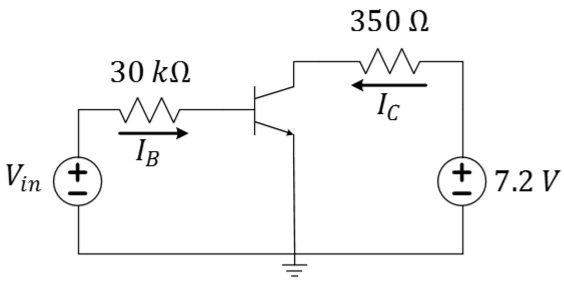




L17Q7: Estimate the operating point (I_C, V_{CE}) when $V_{in} = 1.7\ V$.

L17Q8: What value of V_{in} would drive the transistor to the edge of saturation?

BJT Exercise



BJT datasheet parameters:

- $\beta = 100$
- $V_{BE,on} = 0.7\ V$
- $V_{CE,sat} = 0.2\ V$

L17Q9: What value of V_{in} would drive the transistor to the edge of saturation?

L17Q10: How does your answer change if $30\ k\Omega$ were replaced with $60\ k\Omega$?

L17Q11: How does your answer change if, instead, $350\ \Omega \rightarrow 700\ \Omega$?

Q10:
A. $V_{in@sat}$ goes up
B. $V_{in@sat}$ goes down
C. $V_{in@sat}$ stays the same

Q11:
A. $V_{in@sat}$ goes up
B. $V_{in@sat}$ goes down
C. $V_{in@sat}$ stays the same

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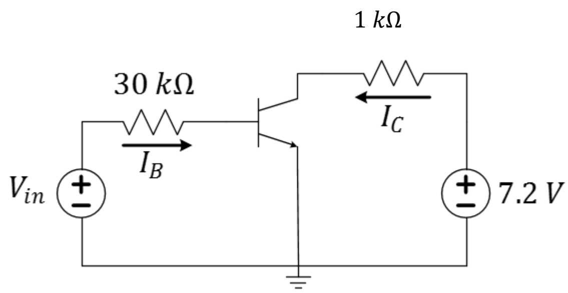
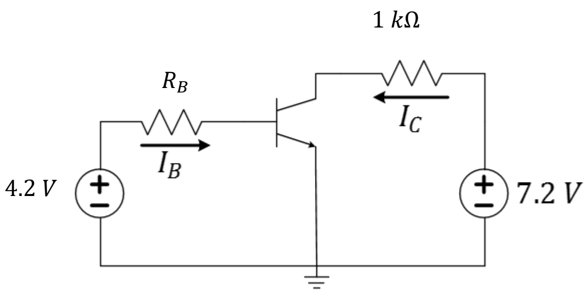
BJT circuit analysis: working back to V_{in}

BJT Datasheet: $\beta = 100, V_{BEon} = 0.7V, V_{CE,sat} = 0.2V$



L17Q12: Find V_{in} such that $V_{CE} = 3\ V$

BJT circuit analysis



BJT Datasheet:

- $\beta = 100,$
- $V_{BEon} = 0.7\ V$
- $V_{CE,sat} = 0.2\ V$

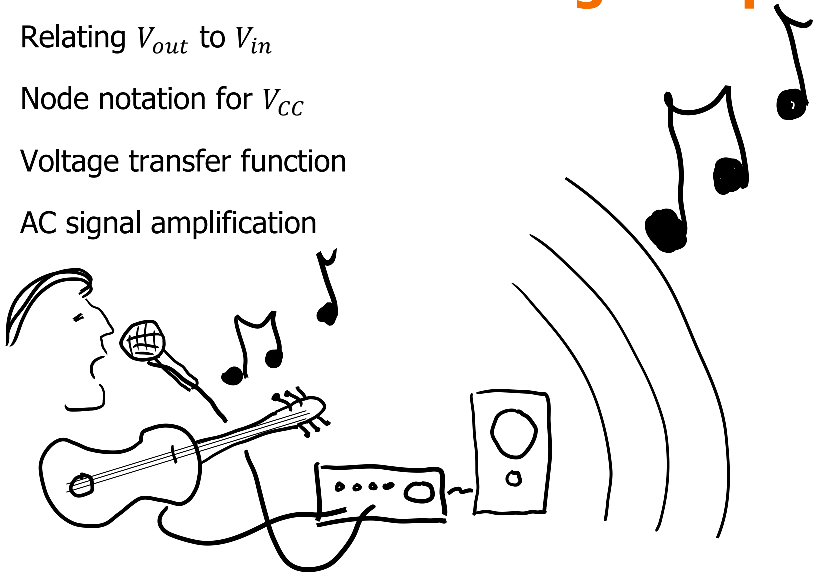
L17Q13: Choose R_B such that the BJT is driven to the edge of saturation.

L17 Learning Objectives

a. Find β and $V_{CE,sat}$ for a given BJT IV characteristic
b. Find V_{CC} and R_C from the IV characteristic of the load line
c. Compute $I_{C,sat}$ from $V_{CC}, V_{CE,sat}$, and R_C
d. Identify the BJT CE operating point given IV characteristics
e. Solve numerically for unknown parameters among $\{V_{in}, R_B, I_B, \beta, V_{BE,on}, V_{CE,sat}, I_C, R_C, V_{CC}, I_{C,sat}\}$ when given some or all of the other values
f. Determine settings to drive transistor into a desired regime

Lecture 18: The BJT Voltage Amplifier

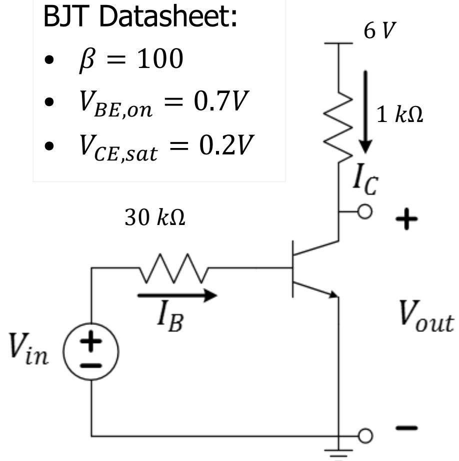
- Relating V_{out} to V_{in}
- Node notation for V_{CC}
- Voltage transfer function
- AC signal amplification



Calculating V_{out} from V_{in} (revisited)

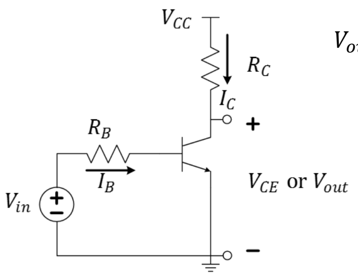
BJT Datasheet:

- $\beta = 100$
- $V_{BE,on} = 0.7V$
- $V_{CE,sat} = 0.2V$



L18Q1: What is $v_{out} = V_{CE}$ for $V_{IN} = 0.3, 1, 2.5, \text{and } 3.5$ Volts?

Review of BJT operating regimes



A. $V_{in} = \frac{V_{CC} - V_{CE,sat}}{R_C}$

B. $V_{in} = V_{CC} + V_{BEon}$

C. $V_{in} = V_{CE,sat} + I_B R_B$

D. $V_{in} = V_{CC} - I_C R_C + I_B R_B$

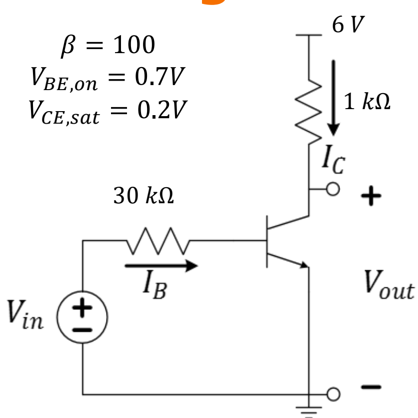
E. $V_{in} = V_{BEon} + \frac{R_B}{\beta R_C}(V_{CC} - V_{CE,sat})$

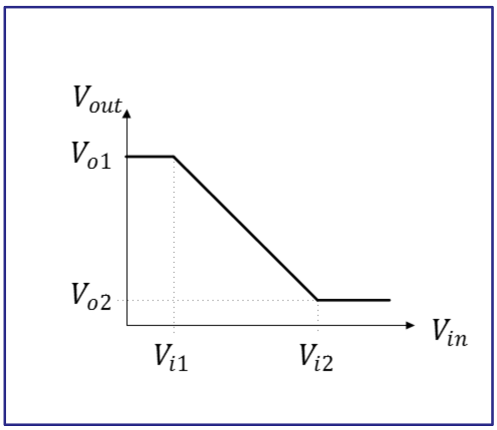
Regime	V_{in}	I_B	I_C	V_C

L18Q2: What is the formula for minimum V_{IN} which causes saturation?

Voltage transfer characteristics

$\beta = 100$
$V_{BE,on} = 0.7V$
$V_{CE,sat} = 0.2V$

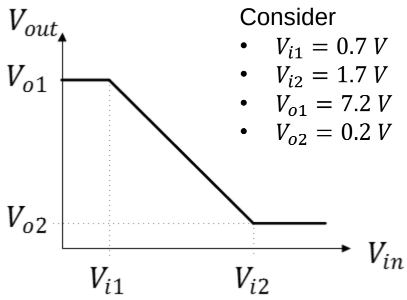




L18Q3: What are the four values $V_{o1}, V_{o2}, V_{i1}, V_{i2}$?

L18Q4: What is the $\frac{\Delta V_{out}}{\Delta V_{in}}$ slope in the active region?

Active regime for signal amplification



Consider

- $V_{i1} = 0.7\ V$
- $V_{i2} = 1.7\ V$
- $V_{o1} = 7.2\ V$
- $V_{o2} = 0.2\ V$

Q7:

A. Active only
B. Cutoff and active
C. Active and saturation
D. Saturation only
E. Cutoff, active, and saturation

L18Q5: If $V_{IN} = 1.2 + 0.2\cos(2\pi 100t)$ what is the equation for V_{out}?

L18Q6: What is different if $V_{in} = 1.2 + 0.6\cos(2\pi 100t)$?

L18Q7: What transistor regimes are entered if $V_{in} = 1.1 + 0.3\cos(\omega t)$?

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L18 Learning Objectives

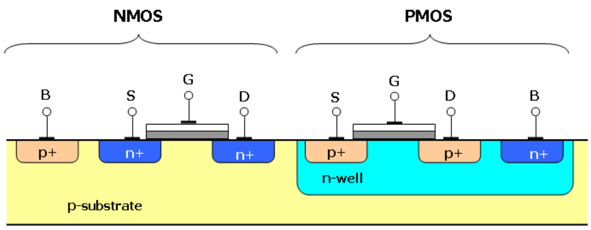
a. Explain the voltage transfer curve (V_{out} vs. V_{in})
b. Find the transition points on the voltage transfer curve
c. Find the slope of the active region in the transfer curve
d. Determine the operating regions for an AC+DC input
e. Evaluate and AC+DC output for linear amplification

Lecture 19: Exercises

- We will use this lecture to catch up, if needed
- We will also do multiple exercises
- Slides may be distributed in lecture

Lecture 20: Field-Effect Transistors (FETs)

- Advantages of MOSFETs for IC manufacturing
- A little physics of MOSFET operation
- MOSFET transistor regimes: operating voltages and current



The Metal-Oxide-Semiconductor FET

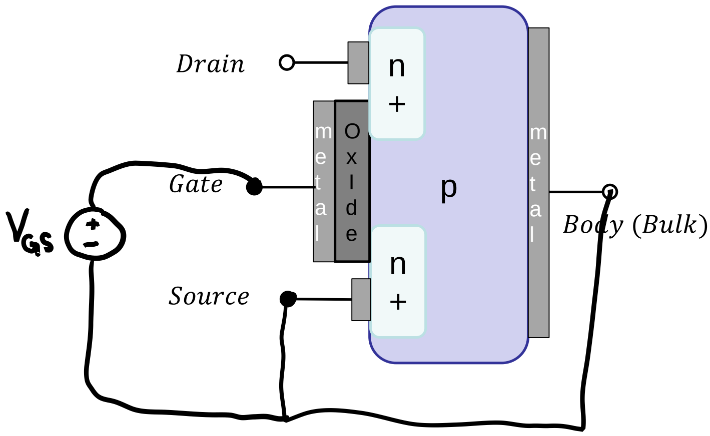
- MOSFETs are **generally** easier to fabricate; also they scale down in size better and use less power than BJTs.
- BJTs are still used in very high-speed switching integrated circuits and they are common as "discrete" devices.

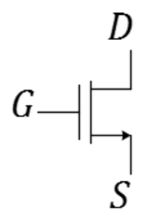
Do you know? How many transistors are in a single modern microprocessor chip?

A. ~100,000
B. ~1,000,000
C. ~10,000,000
D. ~100,000,000
E. ~1,000,000,000

To Produce a Conductive "Channel"

Source and Body are tied together and $V_{GS} > V_{TH} > 0$





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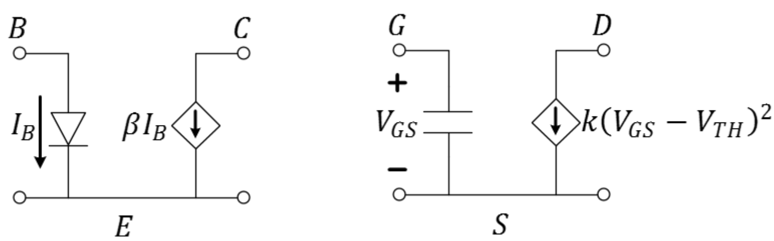
BJT (NPN) vs. MOSFET (n-channel) active region models



Active: $I_C = \beta I_B$

Active: $I_D = k\,(V_{GS} - V_{TH})^2$

ECE Spotlight…

Prof. **Rosenbaum** emphasized in one 2016 paper, the need for physically-accurate circuit models to predict and protect against electrostatic discharge.

Elyse Rosenbaum
University of Illinois

L20Q1: What happens to drain current when $V_{GS} - V_{TH}$ doubles?

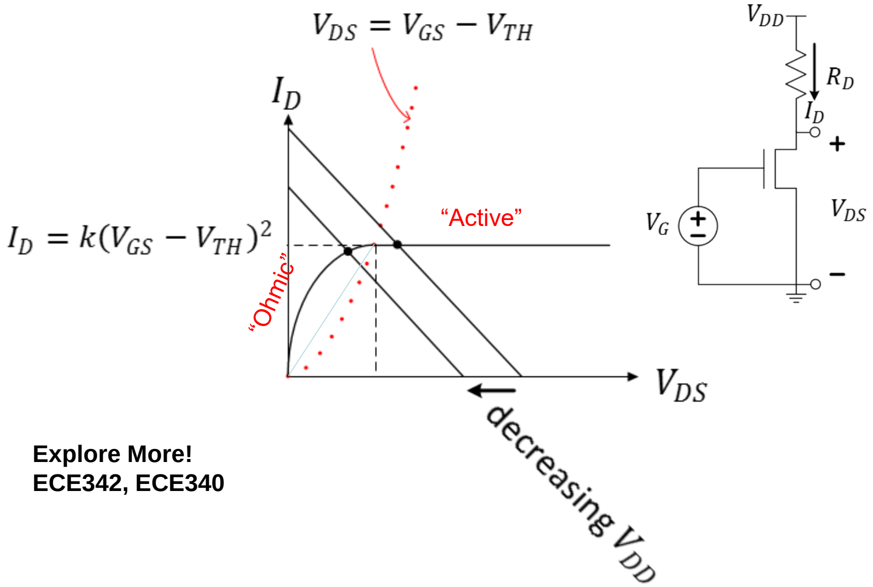
L20Q2: What is the DC current into the gate of the MOSFET model?

L20Q3: What are the units of k?

Q1: the drain current…

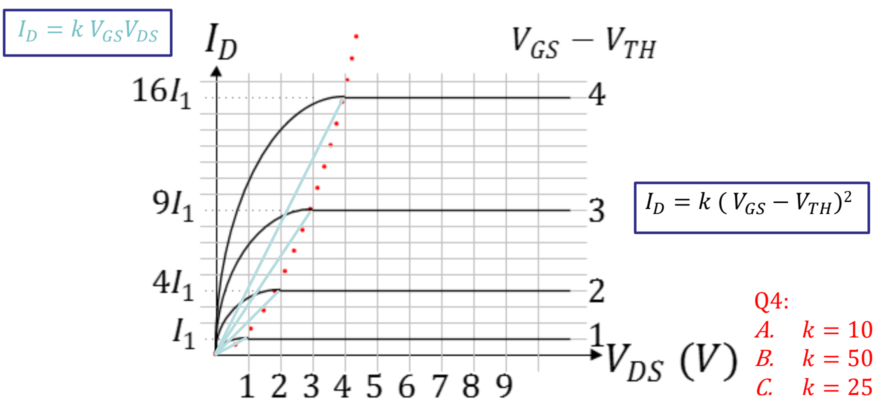
A. halves
B. stays the same
C. doubles
D. triples
E. quadruples

Measuring nMOS IV-curves



Explore More!
ECE342, ECE340

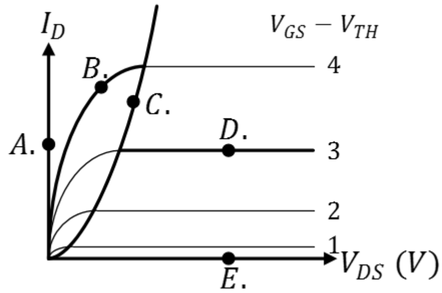
Family of nMOS IV-curves



Q4:
A. $k = 100\ mA/V^2$
B. $k = 50\ mA/V^2$
C. $k = 25\ mA/V^2$
D. $k = 12.5\ mA/V^2$
E. $k = 1\ mA/V^2$

L20Q4: If $I_1 = 100\ mA$, what is the value of k?

nMOS Exercise



L20Q5: At which operating point above would the MOSFET be in "cutoff"?

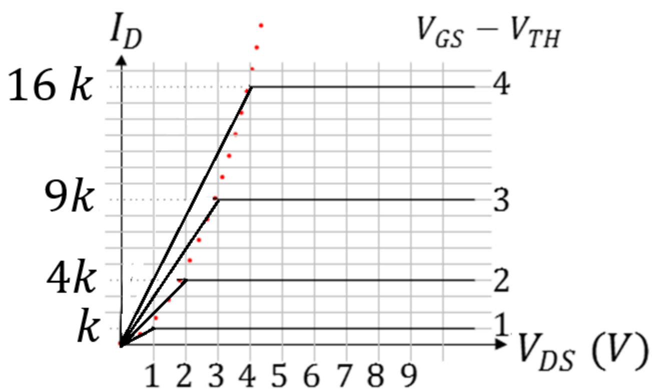
L20Q6: At which operating point above would the MOSFET be "active"?

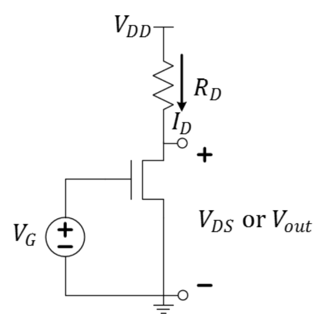
L20Q7: At which operating point above would the MOSFET be "ohmic"?

FET Exercise

FET datasheet:
$\boldsymbol{V_{TH} = 2\ V}$
$\boldsymbol{k = 10\ mA}$

$V_{DD} = 9\ V$
$R_D = 100\ \Omega$
$V_{GS} = 5\ V$



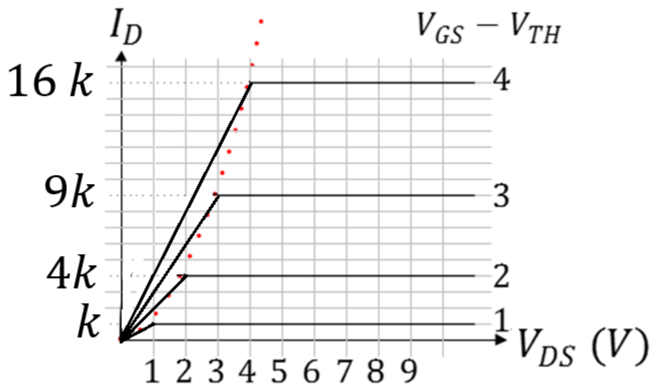


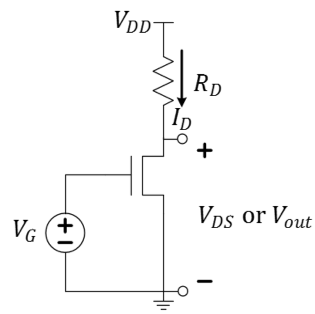
L20Q8: Use the IV plot to find the FET regime and operating point.

FET Exercise

FET datasheet:
$V_{TH} = 2\ V$
$k = 10\ mA$

$V_{DD} = 9\ V$
$R_D = 100\ \Omega$
$V_{DS} = 5\ V$





L20Q9: Find the Gate-to-Source voltage, V_{GS}.

L20. Learning Objectives

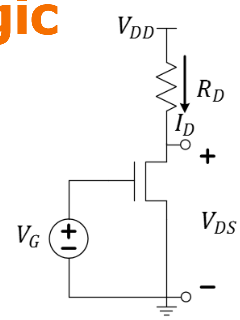
a. To recognize the physics of enhancing/creating a channel in a MOS Transistor

b. To identify the regimes of nMOS with IV curves

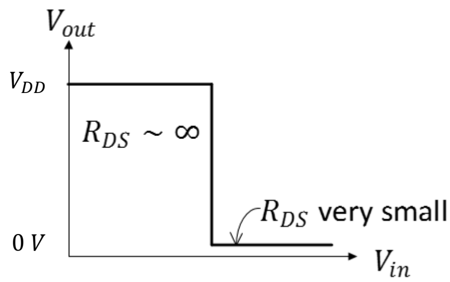
c. To solve nMOS transistor problems using IV data

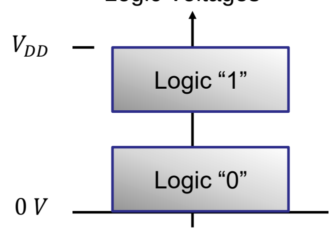
Lecture 21: cMOS Logic

- cMOS logic and circuit models
- cMOS logic circuits and truth tables
- Switching a capacitive load

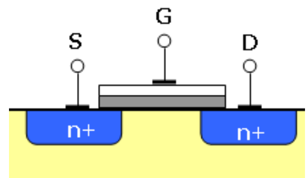


Idealized FET Model:

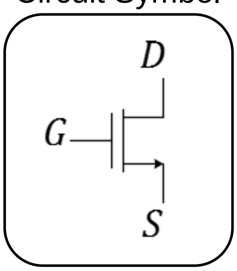




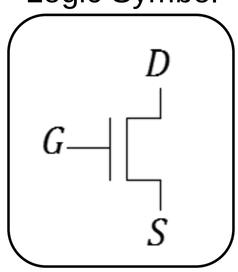
n-channel MOSFET



Circuit Symbol

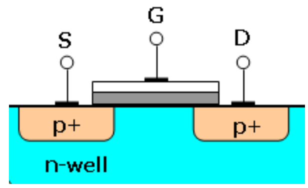


Logic Symbol

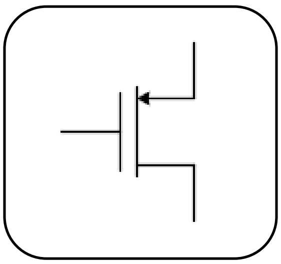


L21Q1: What happens when a logical "1" is applied to the gate?

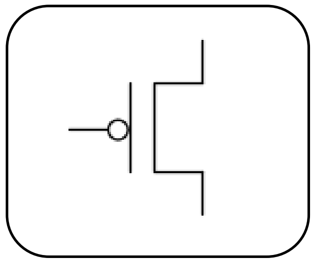
p-channel MOSFET



Circuit Symbol

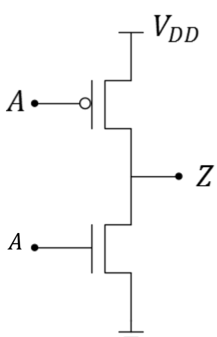


Logic Symbol



L21Q2: What happens when a logical "0" is applied to the gate?

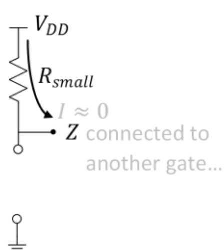
cMOS implementation of Inverter



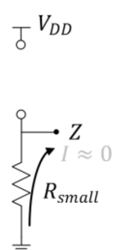
Truth Table:
For *each and every* logical combination of inputs, list the resulting logical output

input	output
A	**Z**
0	
1	

$A = 0$



$A = 1$

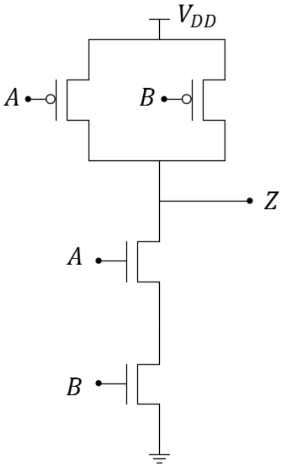


L21Q3: What is the output voltage when the input is connected to V_{DD}?

L21Q4: What is the output voltage when the input is connected to GND?

L21Q5: Complete the Logical "Truth Table".

A Two-Input cMOS Circuit

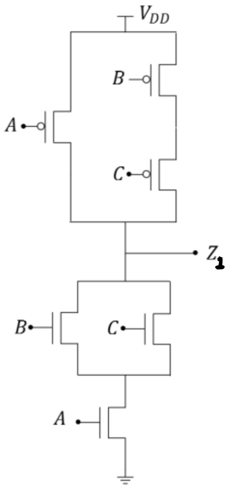


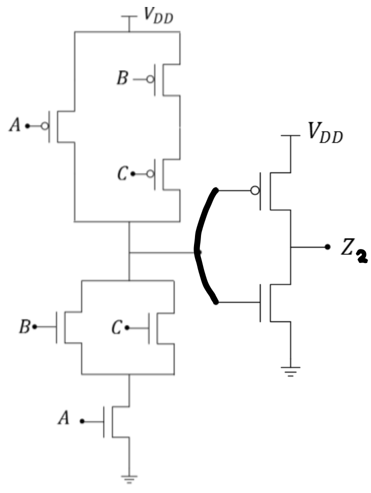
A	B	Z
0	0	1
0	1	ρ
1	0	γ
1	1	0

Q6:
A. $\rho = 0, \gamma = 0$
B. $\rho = 0, \gamma = 1$
C. $\rho = 1, \gamma = 0$
D. $\rho = 1, \gamma = 1$
E. Cannot determine

L21Q6: Complete the Truth Table.

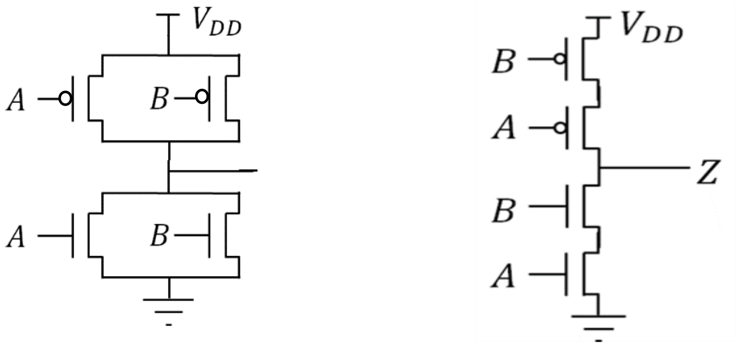
A Three-Input cMOS Circuit





L21Q7: Complete the Truth Tables.

Improperly-Constructed cMOS Circuits



L21Q8: Attempt to complete the Truth Tables.

cMOS Energy

L21Q9: How much energy is stored in each gate ($C = 1fF$) if charged to V_{DD}?

L21Q10: How much energy is consumed from the voltage source to charge it?

Power consumed by a single switching FET

$$P = a\,f\,C\,V^2 n$$

- a – activity factor
- f – switching frequency
- C – load capacitance
- V – switching voltages
- n – number of transistors switching

ECE Spotlight…

Profs. **Pilawa-Podgurski and Hanumolu** work to produce useful circuits with small dimensions that "can be implemented in small area and with minimal power consumption while operating at high [frequency]."


- Largest source of power consumption in computer chips
- Reduction of contributing factors is a technological goal

L21Q11: How many $2\ fF$ caps are switched at $1\ V$ every ns to dissipate $100\ W$?
L21Q12: If the total number of transistors on a chip is 1 billion, what is a?

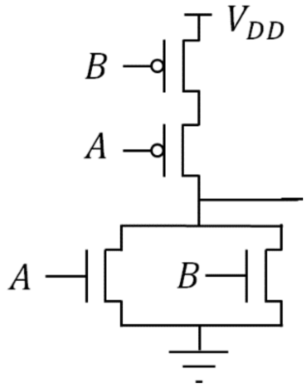
L21. Learning Objectives

a. To explain operation of a cMOS inverter

b. To interpret cMOS logic and express in Truth Table form

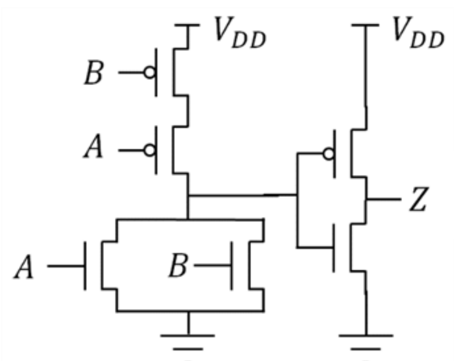
c. To calculate power consumption due to cMOS switching with capacitive loads

Two-Input cMOS Circuit



L21Q13: Complete the Truth Table.

Two-Input cMOS Circuit



L21Q14: Complete the Truth Table.

Lecture 22: Signals, Spectra, and Noise

- Electronic systems and signals
- Spectral representation of signals
- Noise - random fluctuations in signals

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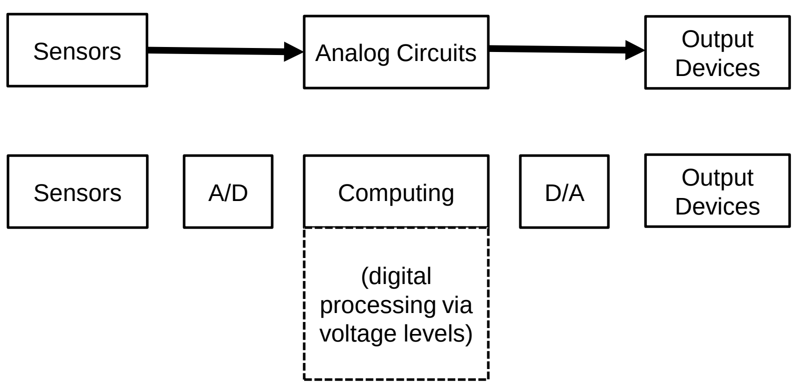
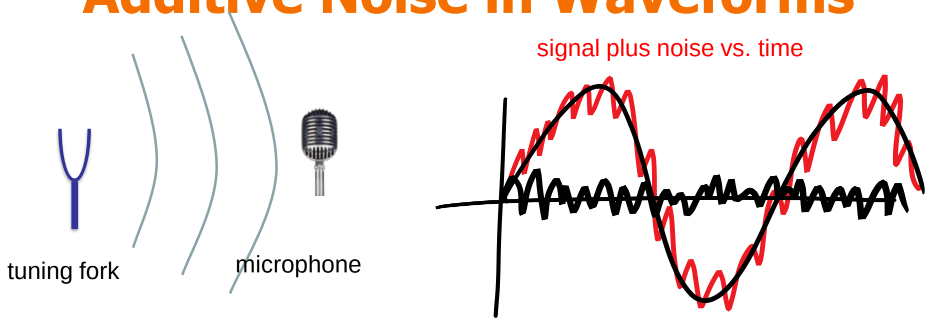
Analog and Digital Systems



What is an analog-to-digital converter?

What is being transferred to each "subsystem"?

Additive Noise in Waveforms



- Even signals that are originally “clean” become noisy
- We consider “additive” noise that “adds on” to desired signals

L22Q1: If the average power of the noise signal is 1 mW (measured across 1 Ohm), what amplitude must a sinusoidal signal have so that the signal-to-noise *power ratio* is equal to 10?

Q1:
$A.\ \approx 10\ mV$
$B.\ \approx 14\ mV$
$C.\ \approx 20\ mV$
$D.\ \approx 100\ mV$
$E.\ \approx 140\ mV$

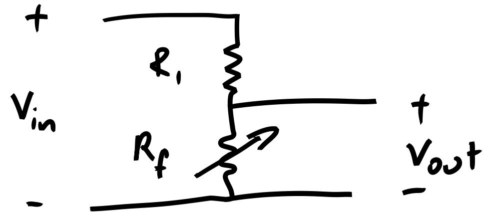
About Noise

Noise is **random** voltage fluctuation

- Thermal movement of electrons is circuit noise
- Power supplies often introduce noise to circuits
- Noise limits the precision of measurements
- Noise limits ability to collect or transfer information
- It is important to limit sources of noise
- Additive noise can be reduced by averaging (filtering)
- Noise can be reduced by advanced signal processing

A Noisy DC Measurement

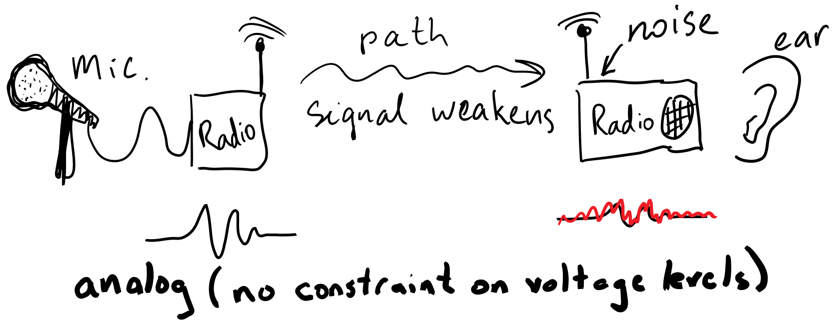
Thermal noise in a sensor circuit can be dominant
- Noise power increases with temperature and resistance
- The average value of the noise is zero



Consider a voltage divider with a flex sensor.

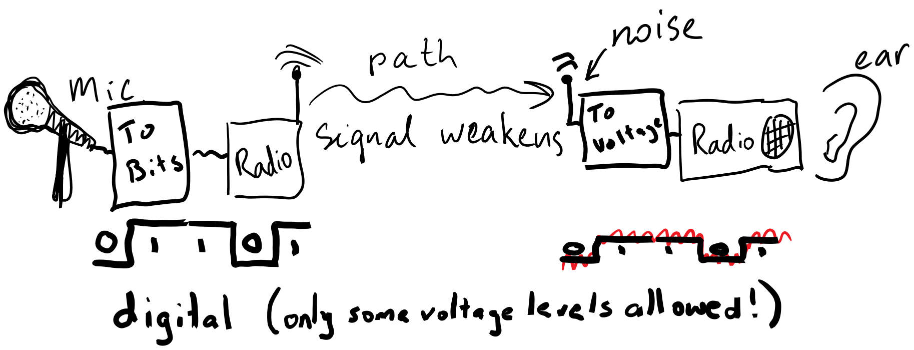
L22Q2: How can we improve the precision of this VDR measurement?

Analog systems suffer from noise



Have you ever heard a noisy radio broadcast?

Noise-Free Digital Communication?



How might you distinguish the different received levels?

Sinusoids Can Represent Analog Signals

- We will represent electrical signals by waveforms $v(t)$
- Any periodic waveform can be represented by sums ($\sum$) of sinusoids (Fourier's theorem/Fourier analysis)

Explore More!
ECE210 (or ECE211)

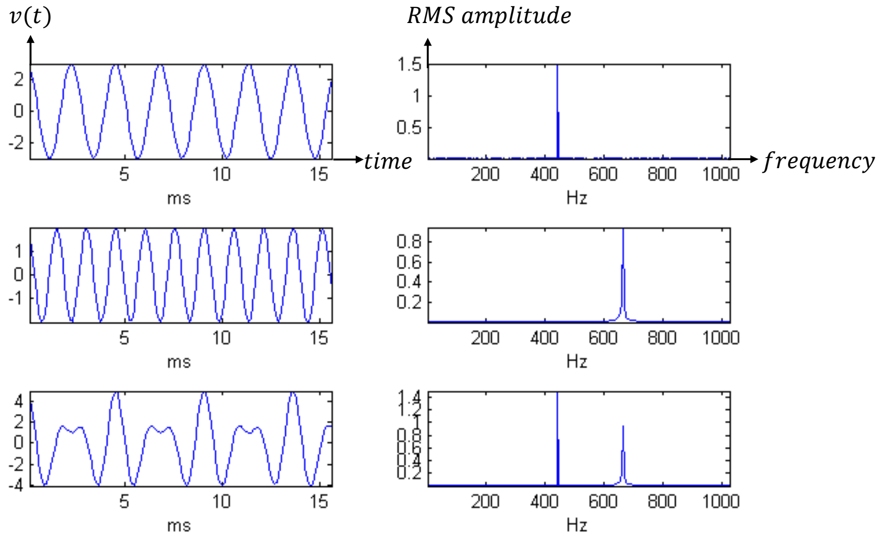
$$v(t) = \sum_k v_k(t) \quad v_k(t) \sim \mathrm{A_k}\cos(2\pi f_k t \qquad)$$

$\mathrm{A}\cos(2\pi f_k t)$ → Unknown System → $\mathrm{A_{new}}\cos(2\pi f_k t + \theta)$

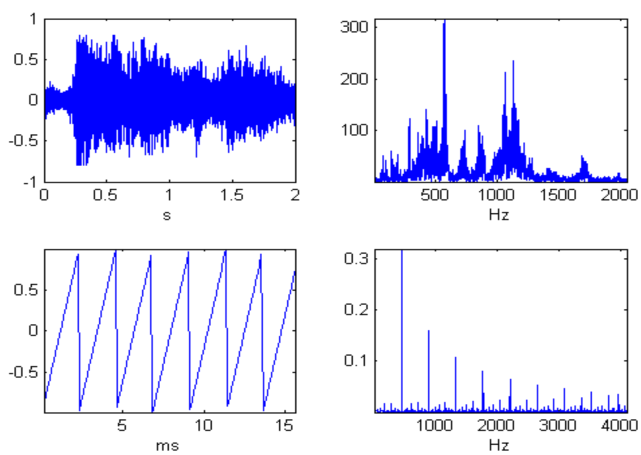
- A "filter" is a system that selectively alters A_{new} at each f_k

L22Q3: What is the frequency of $v(t) = 120\cos(2\pi 200t)$?
L22Q3b: $v(t) = 120\cos(2\pi 200t) + 120\cos(2\pi 400t)$ goes in and $y(t) = 1.2\cos(2\pi 200t) + 240\cos(2\pi 400t)$, what did this filter do?

Spectra of Sinusoids and Sums



Spectra of Other Signals



Listing Frequencies of Periodic Signals

a. $y(t) = \cos(2\,\pi\, 50\, t)$
b. $y(t) = \cos(100\,\pi\, t)$
c. $y(t) = 2\cos(100\,\pi\, t) + 5\sin(100\,\pi\, t)$
d. $y(t) = 3 + 2\cos(100\,\pi\, t) + 5\sin(300\,\pi\, t)$
e. $y(t) = 3 + 2\cos(10\,\pi\, t) + 4\sin(100\,\pi\, t) + 5\sin(3000\,\pi\, t)$

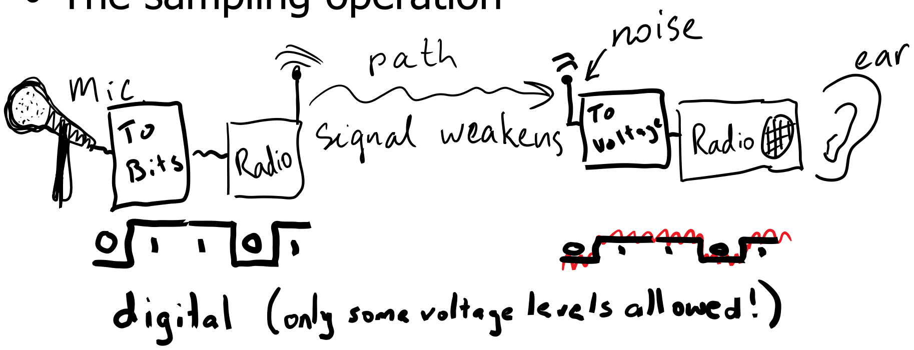
L22Q4: What is the highest frequency in each signal listed above?

Lecture 22: Learning Objectives

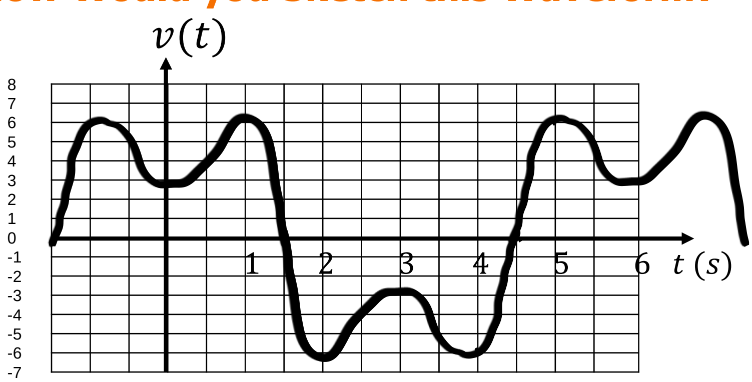
a. Compute RMS voltages from a signal-to-noise power ratio
b. Explain thermal noise and its properties
c. Provide an argument for digital immunity to noise
d. Know basic statement of Fourier's Theorem
e. Identify frequencies in sums of sinusoids
f. Recognize frequency-domain representation of signals

L23: Sampling

- Noise-immunity motivation
- Describing waveforms by samples
- The sampling operation



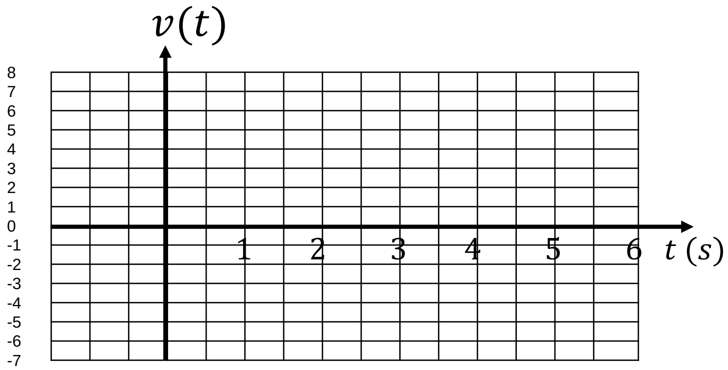
How Would you Sketch this Waveform?



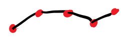
L23Q1: What are the values at $t = 0, 2, 4, and\ 6$ seconds?

L23Q2: Is this enough information to reproduce the waveform?

Enter Data Points of the Previous Waveform.



L23Q3: How should one connect the data points?

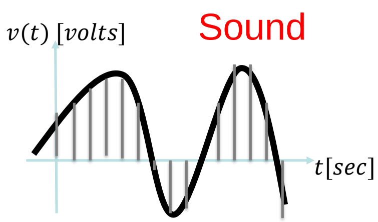
A. Point-to-point with straight lines. 

B. Point-to-point with curvy lines. 

C. Point-to-point, but only with horizontal and vertical lines. 

When storing these values using bits, how many should we use? (NEXT LECTURE!)

Sampling: Sensing real-world data at uniform intervals



T_s: *Sampling period*

$$f_s = \frac{1}{T_s}: Sampling\ Frequency$$

Sampled Sequence:

$$v[n] = v(t = nT_s), n\ integer\ (n = -2, -1, 0, 1, 2, \ldots)$$

Example: $y(t) = 5t\ sampled\ at\ T_s = 2$
Answer: $y[n] = y(nT_s) = 5\text{n}2 = 10\text{n} = \cdots, -20, -10, 0, 10, 20, \ldots$

Sampling

Sampled Sequence:

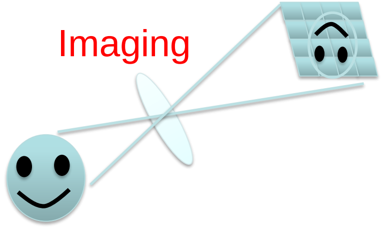
$$v[n] = v(t = nT_s), n\ integer\ (n = -2, -1, 0, 1, 2, \ldots)$$

L23Q4:Let $v_1(t) = 2cos(\pi t)$. Plot $v_1(t)$.

L23Q5:Let $v_1(t) = 2cos(\pi t)$.
If $T_s = 0.5\ s$, what is $v_1[6]$?

L23Q6: Let $v(t) = 5\cos\left(\frac{\pi}{3}t\right) - 2cos(\pi t)$.
If $T_s = 0.5\ s$, what is $v[6]$?

Sampling: Sensing real-world data at uniform intervals



Think About It! How does sampling work in digital photography?

Largest Sampling Period, T_S

If you sample fast enough to catch the highs/lows on a wiggly waveform, **then** you can smoothly reconnect the data points to recreate it.

L23Q7: Speech is intelligible if frequencies up to 3.5 kHz are preserved. What should we use for T_S?

A. $< \frac{1}{7}\ ms$
B. $< \frac{1}{3.5}\ ms$
C. $< 3.5\ ms$
D. $> 3.5\ ms$
E. $> 7\ ms$

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L23: Learning Objectives

a. Explain the motivation for digital signals
b. Determine reasonable sampling interval for plotted waveforms
c. Sample an algebraic signal given a sampling interval

L24: Preserving Information in A/D

- Nyquist Rate
- Quantization
- Memory Registers
- Binary Numbers
- Aliasing
- A/D block diagram
- D/A block diagram

Nyquist Rate: lower bound on f_s

A sampled signal can be converted back into its original analog signal without any error if the sampling rate is more than twice as large as the highest frequency in the signal.

$$\boxed{f_s > 2f_{max}}$$

☺No loss of information due to sampling☺

Interpolation: recreate analog with a special function!

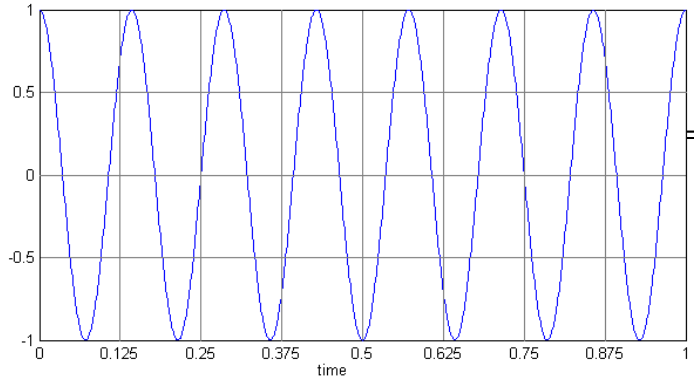
L24Q1: Speech is intelligible if frequencies up to 3.5 kHz are preserved. What is the Nyquist rate?

L24Q2: Music is often filtered to include sounds up to 20 kHz. What sampling rate should we use?

Q1:
A. 1.75 kHz
B. 3.5 kHz
C. 5.25 kHz
D. 7 kHz
E. 8 kHz

Aliasing occurs when Sampling is sparse

When f_s is too small (T_s is too large), high-frequency signals masquerade as lower frequency signals…

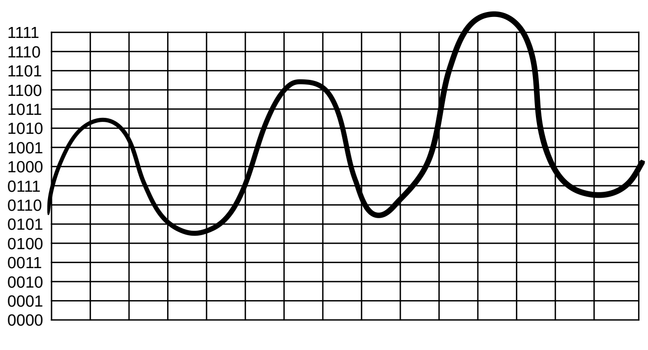


$\cos(2\pi 7t)$

$\Rightarrow f_{max} = 7\ Hz$

L24Q6: When sampling at $f_s = 8\ Hz$, what is the frequency of the signal above after reconstruction?

Quantization:
Round voltage values to nearest discrete level



L24Q3: Assume we sample at the vertical lines. Digitize the waveform using four-bit samples.

Computers are made of cMOS Circuits

- **Registers** are combinations of logic circuits that utilize electrical **feedback** to serve as computer's working memory.
- Each register element is a bit which can be 0 (low) or 1 (high)
- Example: An 8-bit register holds 8 binary values.

Choose the largest 8-bit binary value.

A. 00001011
B. 00010110
C. 00010000
D. 00001111
E. 00000101

Binary Numbers

Any number system has a base, N, with N digits $\{0, \ldots, N-1\}$, and n-digit number representations with the distance from the decimal point indication what base power each digit represents.

3-digit Binary integers:

$$\begin{array}{llll} \mathbf{0}: & 0 & 0 & 0 \\ \mathbf{1}: & 0 & 0 & 1 \\ \mathbf{2}: & 0 & 1 & 0 \\ \mathbf{3}: & 0 & 1 & 1 \\ \mathbf{4}: & 1 & 0 & 0 \\ \mathbf{5}: & 1 & 0 & 1 \\ \mathbf{6}: & 1 & 1 & 0 \\ \mathbf{7}: & 1 & 1 & 1 \end{array}$$

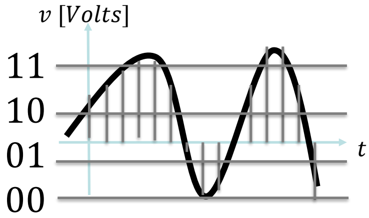
Base 10: What is the number 51?

$$\begin{array}{rcc} 2-digit\ number: & 5 & 1 \\ position\ (in\ decimal): & 10s\ place & 1s\ place \\ meaning\ (in\ decimal): & 5 \times 10 + & 1 \times 1 \end{array}$$

Base 2: What is the number 101_2?

$$\begin{array}{rccc} 3-digit\ number: & 1 & 0 & 1 \\ position\ (in\ decimal): & 4 & 2 & 1 \\ meaning\ (in\ decimal): & 1 \times 4 + & 0 \times 2 + & 1 \times 1 \end{array}$$

More bits=More levels= Less Quantization Error (Noise)

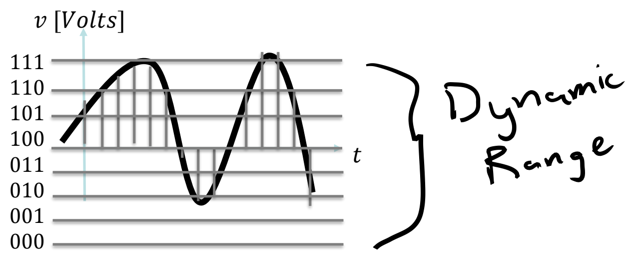


Example: 2 − bit quantizer

$$e[n] = v[n] - v_Q[n]$$

L24Q4: If the voltages 2.93 and 5.26 are quantized to the nearest 0.25 V, what are the quantization errors?

3-Bit Quantizer

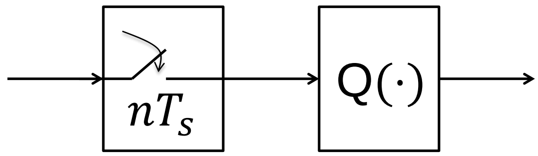


Example: 3 − bit quantizer

L24Q5: How many levels in a 10-bit quantizer?

A. 4
B. 8
C. 10
D. 100
E. 1024

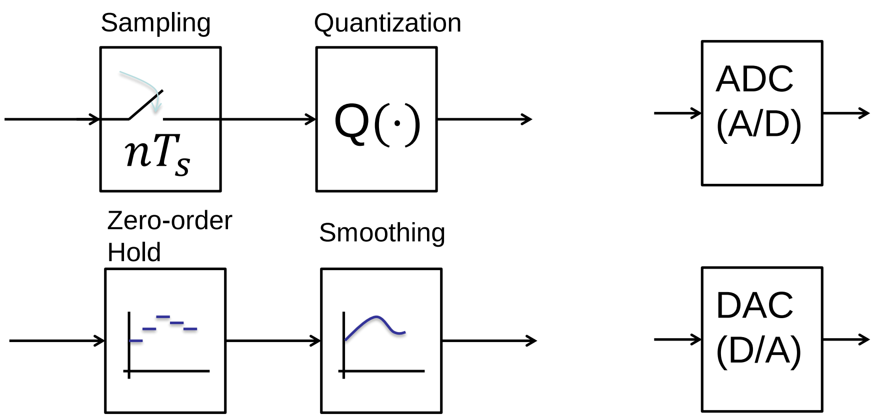
Sampling + Quantization =Digitization



- $Sampling\ Rate = 1/(Sampling\ Period)$ $\quad f_s = \frac{1}{T_s}$
- $\uparrow Sampling\ Rate \Rightarrow \uparrow Memory\ usage$
- $\downarrow Sampling\ Rate \Rightarrow Loss\ of\ Information?$

L24Q7: Under what conditions on sampling and on quantization will you incur a loss of information?

Analog-to-Digital Converter Digital-to-Analog Converter



The zero-order hold results in an analog voltage. What circuit parts might a smoothing filter contain?

A. Resistors B. Capacitors C. Diodes D. BJTs E. MOSFETs

Exercises

L24Q8: CD-quality music is sampled at 44.1 kHz with a 16-bit quantizer. How much memory (in Bytes) is used to store 10 seconds of sampled-and-quantized data?

L24Q9: CD-quality music is sampled at 44.1 kHz with a 16-bit quantizer. It is stored on a 700 MB CD. How many minutes of music do you predict a single CD can hold? (Does your answer account for stereo?)

L24Q10: Digital voice mail samples at 8 kHz. 32 MB of memory is filled after 3200 seconds of recording. How many bits of resolution is the quantizer utilizing?

L24: Learning Objectives

a. Convert a voltage series to a quantized (bit) representation
b. Solve problems involving sampling rate, quantizer size, memory size, and acquisition time
c. Find the Nyquist rate of a signal given its highest frequency
d. To be able write out binary integers numbers in increasing value
e. Describe the implications for sound quality based on sampling rate and quantization depth (# bits in quantizer)

L25: Quantifying Information

- Define Information
- Exploring Information-sharing games
- Quantifying Information
  - Informally via intuition
  - Formally via **Entropy**
- To use relative frequency to compute entropy, the shortest theoretical average code length.

What is Information?

Information: a)That which informs.
b) Unknown items drawn from a set.

Implies an amount of uncertainty.

Examples:

- Letters from an alphabet
- Words from a dictionary
- "voltages" entering an A/D
- Image pixel values from your camera

The Game of Twenty Questions

I have information for you.

What is it?

Guess!

Can I ask yes/no questions?

OK. You can ask 20 of them. Use them wisely.

If you have ever played this against a computer, it is amazing at how quickly the computer guesses your thought…or is it?

Q1
A. One
B. Two
C. Three
D. Four
E. Five

Q2
A. 20
B. 400
C. 2096
D. Over 1 Million
E. Over 1 Billion

L25Q1. I am thinking of a color in the set {blue, yellow, red, green}. How many Yes/No questions will it take to guess my color?

L25Q2: How many items (in a set) could be distinguished by 20 Yes/No questions?

Quantifying Information

The “amount” of data might not represent the magnitude of the information it contains. If you can **predict** data, it contains less information.

L25Q3: Which contains more information, the samurai cartoon or the samurai photo?

Consider these information sets:
- {blue, yellow, red, green}
- {blue 50%, yellow 20%, red 15%, green 15%}
- {blue 100%}


from Wikipedia

L25Q4: For which set is the unknown color most predictable?

L25Q5: For each set, how many questions will it take, on average, to guess the color?

L25Q6: For which set is more information being transferred by the question game?

Entropy measures Information

The entropy, H, of a **message** can be computed given the statistical frequencies, the p_i of each i^{th} possibility (a.k.a. the probability of each message in the set of possible messages)

$$H = \sum_{i=1}^{N} p_i \times (-\log_2(p_i)) = \sum_{i=1}^{N} p_i \times \log_2\left(\frac{1}{p_i}\right)$$

in units of "bits"!

L25Q7: What is the entropy in a result of a single flip of a fair coin?

L25Q8: What is the entropy of a number of "heads" in two coin flips?

Review of logarithms and properties

- Base-2 logarithm gives a power of 2 equivalent for a number:
  $$x = \log_2 \boldsymbol{A} \quad \Rightarrow \quad \boldsymbol{A} = \boldsymbol{2^x}$$
- Logarithm of an inverse of a number is negative log of the number:
  $$\log_2 \frac{\mathbf{1}}{\boldsymbol{A}} = -\log_2 \boldsymbol{A}$$
- Logarithm of a product is the sum of two logarithms:
  $$\log_2 \boldsymbol{AB} = \log_2 \boldsymbol{A} + \log_2 \boldsymbol{B}$$
- Logarithm of a ratio is the difference of two logarithms:
  $$\log_2 \frac{\boldsymbol{A}}{\boldsymbol{B}} = \log_2 \boldsymbol{A} - \log_2 \boldsymbol{B}$$

$\boldsymbol{A}$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
$\sim\log_2 \boldsymbol{A}$	0.0	1.0	1.6		2.3		2.8				3.5		3.7		

L25Q9: Complete the above table using logarithm properties.
L25Q10: What is $\log_2 \frac{\mathbf{24}}{\mathbf{105}}$?

Entropy of the Class by Major

S	ECE	IE	GE	DGS
p	200/400	50/400	50/400	100/400

Considering only the 4 most-represented disciplines, suppose that a selected sample of 400 ECE110 students produces the student population shown above.

L25Q11: What is the probability that a student selected from this group is an IE?

L25Q12: What is the entropy of any student's department taken from this set?

L25: Learning Objectives

a. To comparative the amount of information contained in slightly different data sets
b. To compute base-2 logarithms using log properties
c. To compute Entropy (information) in units of bits given the relative frequency of each item in a set

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Entropy of the Class by Major

S	ECE	IE	GE	DGS	Other
p	200/450	50/450	50/450	100/450	50/450

Including a category of "Other", the student population by major now takes on the statistics shown above.

L25Q13: What is the probability that a student selected from this group is an IE?

L25Q14: What is the entropy of any student's department taken from this set?

L25Q15: What would have been the entropy if all 5 categories were equally represented by the course's student body?

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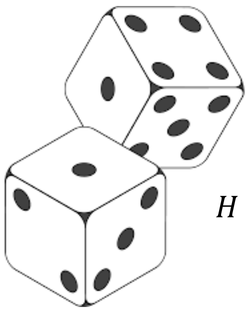
Entropy of the sum of two dice

	1	2	3	4	5	6
1	2	3	4	5	6	7
2	3	4	5	6	7	8
3	4	5	6	7	8	9
4	5	6	7	8	9	10
5	6	7	8	9	10	11
6	7	8	9	10	11	12



$$H = \sum_{i=1}^{N} p_i \times \log_2\left(\frac{1}{p_i}\right)$$

S	2	3	4	5	6	7	8	9	10	11	12
p	1/36	2/36	3/36	4/36	5/36	6/36	5/36	4/36	3/36	2/36	1/36

L25Q16: What is the entropy of the sum of two dice?

L25Q17: Compare this to the entropy of one out of eleven equally-likely outcomes. Without doing any calculations, which value should be larger (carry more information)?

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L26: Compression

- Lossless vs. lossy compression
- Compression ratios and savings
- Entropy as a measurement of information
- Huffman code construction and decoding

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Data Compression Ratio and Savings

- Data Compression Ratio (DCR)

$$DCR = \frac{\#\ of\ bits\ in\ original\ data}{\#\ of\ bits\ in\ compressed\ data} = \frac{original\ data\ rate}{compressed\ data\ rate}$$

- Savings: $S = 1 - \frac{1}{DCR}$ *(x100 for %)*

L26Q1. Stereo audio is sampled at 44.1 kHz and quantized to 16 bits/channel and then compressed to 128 kbps mp3 playback format. What are the approximate DCR and the resulting savings?

L26Q2. A picture of a samurai was saved as a 24-bit samurai.bmp (full size, 2188 kB) and a 31 kB samurai.png. Estimate the DCR and savings from the PNG compression.

Q2: DCR~
A. 10
B. 30
C. 50
D. 70
E. 100

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Lossy and Lossless Compression

- Lossy Compression
  - Usually leads to larger DCR and savings
  - Sometimes creates noticeable "artifacts"
  - Examples: mp3, mpeg, jpeg
- Lossless Compression (keeping all information)
  - Uses repetition or other data statistics
  - Usually leads to smaller compression ratios (~2)
  - Examples: PNG, run-length codes, Huffman codes…

from Wikipedia

L26Q3. Why was the cartoon samurai picture highly compressible?
L26Q4: Can we expect to achieve such DCR with the photograph?

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Super-Fast Sandwiches, Order-By-Number Menu

Menu:	#1	#2	#3	#4	#5
Number of orders	18	8	9	10	5

The number of orders during the lunch hour for each menu item is listed above.

L26Q5: What was the relative frequency (probability) of someone ordering the menu's #1 sandwich selection (we call this p_1)?

L26Q6: What is the fewest number of bits needed to encode each of 8 possible orders with a unique (and unambiguous) bit sequence for each?

L26Q7: What is the entropy of one order given the popularity statistics above?

Huffman Codes use bits efficiently

Menu:	#1	#2	#3	#4	#5
Number of orders	18	9	8	10	5

Use fewer bits for more common **symbols**. Here's how:

1. Order the symbols from most frequent on left to least frequent on right.
2. From the two least frequent symbols, create two "branches" that connect them into a single end **nodes** of a **tree graph**.
3. Mark the least frequent branch/node with a "0" and the most frequent a "1"
4. Consider these two symbols be one new symbol with the combined frequency. Record this new frequency of the new node and return to step 1 (or step 2), considering nodes as new symbols.

L26Q8: Create a Huffman tree based on the order statistics given above.

Encoding and decoding Huffman

Menu:	#1	#2	#3	#4	#5
Number of orders	18	9	8	10	5
Huffman Code					

Huffman Codes are **prefix-free**! (If you know where the message starts, you can separate the symbols without confusion.)

L26Q9: Complete the table above with Huffman codes from the tree above.
L26Q10: Which menu items does not appear in the sequence 111000010100?

A. #1
B. #2
C. #3
D. #4
E. #5

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You can't beat Entropy!

The average lossless-code length is never less than entropy. Given N symbols $S_1, S_2, \ldots S_N$ and corresponding frequencies, p_i, the average length per symbol is

$$L_{avg} = \sum_{i=1}^{N} p_i \times L_i$$

$$L_{avg} \geq H$$

L26Q11: What is the average bit length per sandwich order?

L26Q12: How does the average bit length compare to entropy?

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L26: Learning Objectives

a. Compute compression ratio and savings
b. To use relative frequency to compute entropy, the shortest theoretical average code length
c. To encode a symbol set with a Huffman code
d. To decode a Huffman-encoded message
e. To compute average code length for given a code

Lecture 27: Exercises

- We will use this lecture to catch up, if needed
- We will also do multiple exercises
- Slides may be distributed in lecture

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Lecture 28: Photodiodes and Solar Panels

- The nature of light
- Photon absorption in semiconductors
- Photocurrent in diodes and its use
  - Detecting light and signals
  - Generating electrical energy
- Energy from solar panels

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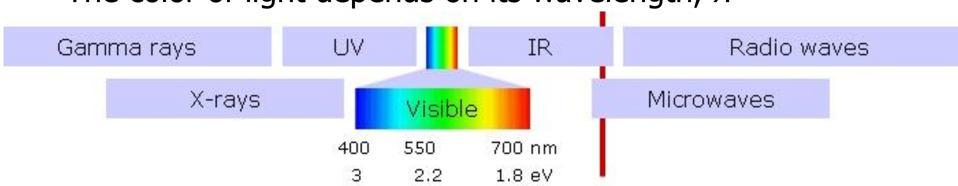
Light consists of (Energetic) Photons

- Photons are sometimes called wave packets
- Each photon (of wavelength λ in *nm*) carries an amount of energy

$$E = \frac{1240}{\lambda}\left[\frac{eV}{photon}\right]$$

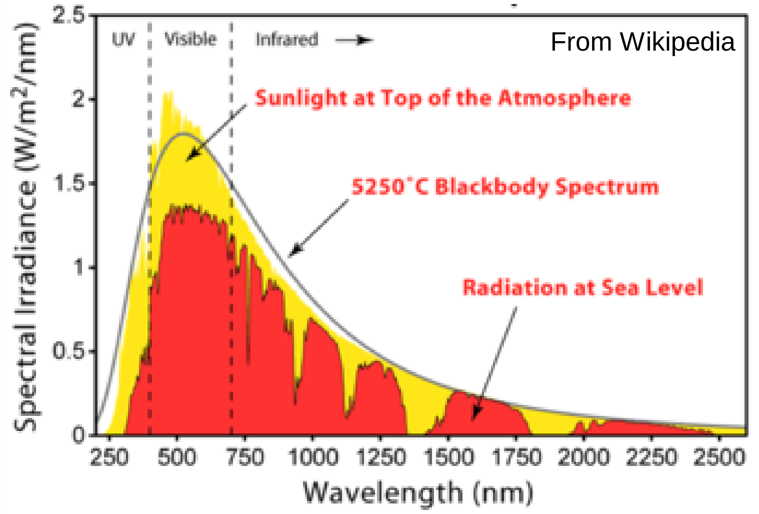
$1\ eV$ is equivalent to $1.6 \times 10^{-19}\ J$

- The color of light depends on its wavelength, λ



L28Q1: How many photons per second are provided by a 1 mW 650 nm laser?

Available Solar Energy (Radiation Spectrum)



Pick the closest answer:

A. $1\ W/m^2$
B. $10\ W/m^2$
C. $100\ W/m^2$
D. $1000\ W/m^2$
E. $10\ kW/m^2$

L28Q2: Estimate the solar irradiance (W/m^2) at sea level (hint: total red area).

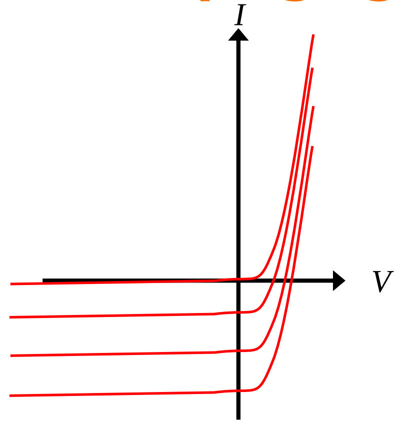
Creating electron-hole pairs in Semiconductors

- An electron in a material can absorb a photon's energy
- An electron can sometimes lose energy to emit a photon
- Semiconductor electrons have a gap in allowed energy, E_g
- Photons with energy bigger than the gap are absorbed
- Absorbed photons can create usable electrical energy

L28Q3: What is the maximum wavelength absorbed by Si ($E_g = 1.1\ eV$), by GaN ($E_g = 3.4\ eV$), and by diamond carbon ($E_g = 5.5\ eV$)?

Photodiode IV depends on impinging Light

- Reverse bias mode
  - Photodetector
  - Detecting light signals
  - Energy is dissipated
- Forward bias mode
  - Photovoltaic cell
  - Energy is generated



L28Q4: Sparkfun's BPW34 photodiode generates 50 µA of current when reverse-biased and illuminated with 1 mW/cm^2 at 950 nm. If a 1 mW 950 nm laser is focused on the photodetector, what is the resulting photocurrent?

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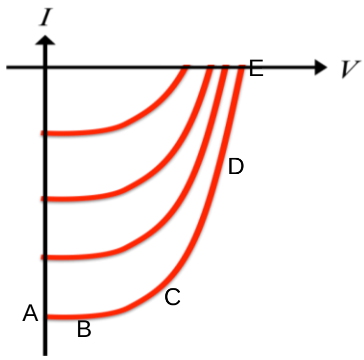
Photovoltaic operation collects Energy

- Forward-bias mode
- $P = IV$ is supplied
- Maximum power point
- $P_{max} = I_m V_m = FF\ I_{sc} V_{oc}$
- Typical FF = 70%



L28Q5: Identify the P_{max} point above

L28Q6: If Sparkfun's BPW34 photodiode has $I_{SC} = 40\ \mu A$ and $V_{OC} = 350\ mV$ when illuminated with 1 mW/cm^2 at 950 nm, and the fill factor is 50% what is the maximum power produced?

Solar panels as energy sources

L28Q7: Assuming 500 W/m^2 solar irradiance and a 25% efficient solar panel, how much roof area should be covered to supply 50A at 120V?

L28Q8: Given an average of 5 hours of sunshine per day and a utility cost of $0.11/kWh how much of the utility cost can such a solar panel save?

ECE Spotlight…

ECEB is aspiring to a Net Zero Energy rating and targeting LEED Platinum certification from the U.S. Green Building Council. You should look into the project to learn how it is being achieved. Do some of your own number crunching!

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Lecture 28 Learning Objectives

a. Relate photon flux (photons/sec) to power and wavelength
b. Calculate maximum absorbed wavelength for a band gap
c. Sketch photodiode IV curve and explain operating regimes
d. Calculate reverse bias current for incident light power
e. Calculate maximum power from IV intercepts and fill factor
f. Estimate power (and its $ value) produced by a solar panel

Lecture 29: Course Review

- If you have a request that a specific question or topic be covered on this day, please email your instructor.
- Other questions will focus on *muddy points*.
- More info TBA.

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Appendix on Ethics

Ethical views can have multiple origins:

- Value-based
- Relationship-based
- Code-based

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Courses Dealing with Engineering Professionalism and Ethics

- Ethics across the curriculum in electrical and computer engineering: class sessions in ECE 110, ECE 445
- Class sessions in other engineering programs: CEE 495, GE 390, MSE 201, ME 470
- CS 210, Professional and Ethical Issues in CS
- ECE/PHIL 316, Ethics and Engineering
  - Elective
  - Gen ed: advanced composition, humanities

What is professional responsibility?

Engineering professional responsibility encompasses the ethical obligations of engineers in their professional relationships with clients, employers, other engineers, and the public; these obligations include honesty and competence in technical work, confidentiality of proprietary information, collegiality in mentoring and peer review, and above all, the safety and welfare of the public, because engineers' decisions can significantly affect society and the environment. –*Prof. M. Loui*

L4Q4: What ethical viewpoint is represented above?
A. Values B. Relationships C. Code

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Engineers have many ethical obligations

- Relationships with clients
  - Competence
  - Honesty
- Relationships with employers
  - Conflict of interest
  - Confidentiality, e.g., trade secrets
  - Individual and collective responsibility
  - Loyalty, whistle-blowing
- Relationships with other professionals
  - Licensing, due credit
  - Collegiality, mentoring
- Relationships with the public
  - Public understanding of technology
  - Social impacts of technology

IEEE Code of Ethics (2012)

IEEE – Institute of Electrical and Electronics Engineers

We, the members of the IEEE, in recognition of the importance of our technologies in affecting the quality of life throughout the world, and in accepting a personal obligation to our profession, its members and the communities we serve, do hereby commit ourselves to the highest ethical and professional conduct and agree:

IEEE Code of Ethics (2012)

1. to accept responsibility in making decisions consistent with the safety, health, and welfare of the public, and to disclose promptly factors that might endanger the public or the environment;
2. to avoid real or perceived conflicts of interest whenever possible, and to disclose them to affected parties when they do exist;
3. to be honest and realistic in stating claims or estimates based on available data;
4. to reject bribery in all its forms;
5. to improve the understanding of technology, its appropriate application, and potential consequences;

IEEE Code of Ethics (2012)

6. to maintain and improve our technical competence and to undertake technological tasks for others only if qualified by training or experience, or after full disclosure of pertinent limitations;
7. to seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors, and to credit properly the contributions of others;
8. to treat fairly all persons regardless of such factors as race, religion, gender, disability, age, or national origin;
9. to avoid injuring others, their property, reputation, or employment by false or malicious action;
10. to assist colleagues and co-workers in their professional development and to support them in following this code of ethics.

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Case Study

Occidental Engineering…search at Santa Clara University:

http://www.scu.edu/

- Break into groups or pairs and discuss.
  - Consider the issue from the viewpoint of all people involved
  - Consider the options and the consequences of each
  - Can your group come to a single path of action?